A SYSTEMS APPROACH TO ASSESS AND IMPROVE THE LAST-MILE ACCESS TO MASS TRANSITS

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DECLARATION

I hereby declare that the thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information that have been used in the thesis. This thesis has also not been submitted for any degree in any university previously.

Ashwani Kumar
31st August 2015

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Summary

Rapid urbanization, coupled with increasing private motorization, poses serious challenges to urban mobility. Development of mass rapid transits and promotion of non-motorised modes, like cycling and walking, are widely considered as possible solutions. However, ridership on many mass transit systems is much lower than the projected estimates mainly due to poor accessibility of the stations. Taking a systems perspective, we explore ways in which the last-mile access can be improved and further try to develop methods to assess it. As cycling is considered a cheap and efficient mode for accessing transit stations, we develop a framework to assess effectiveness of different cycling-related policies in promoting commuter cycling and examine the potential of cycling as one of the means of improving last-mile access by studying in detail the case of Singapore. We apply analytics on farecard data in Singapore to estimate last-mile cycling potential through spatio-temporal visualisation of fare-card data and further develop an optimization model to strategize investments in cycling infrastructure.

Next, we conduct a study of Delhi metro to obtain a better understanding of the factors that determine the attractiveness of the rail transit systems and identify some of the ways to increase the ridership by improving the last-mile access. We also develop a simple optimization approach to choose a portfolio of last-mile scenarios for network-wide maximization of benefits. Finally, we develop and visualize indices to measure the state of last-mile access to transit stations and show their application in different contexts for a variety of objectives through the case studies and comparisons between Singapore and Delhi.

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Chapter-1

Introduction

Background

The world is urbanizing rapidly. The world's urban population is projected to rise by 75% during the next four decades, from 3.6 billion in 2011 to more than 6.3 billion in 2050, with most growth happening in big and medium-sized cities, especially in the developing countries (United Nations 2012). This development, coupled with increasing private motorization, has directly led to deteriorating traffic conditions and indirectly to economic and social costs including time lost in traffic, extra fuel consumption, pollution, and lower quality of life in cities.

Different approaches have been adopted in different cities to improve urban mobility. On the supply side, augmentation of road infrastructure, streamlining of traffic flows and improvements in public transport are some of the popular responses. Some cities, particularly in Europe, have also laid emphasis on specialized infrastructure to facilitate non-mechanized modes like cycling. Many cities have also successfully implemented or experimented with transport demand management (TDM) policies like congestion pricing, vehicle quotas and parking restrictions, to discourage use of private cars. There are also examples of policy interventions promoting higher occupancy in vehicles like exclusive bus lanes, high occupancy vehicle (HOV) lanes and ride sharing. However, TDM policies are difficult to implement politically and require technological interventions. Besides, easy access to a good public transport system is a pre-requisite to implement TDMs.

There is no panacea to solve the challenges in urban mobility. However, right policies, if implemented in unison, can help alleviate many of the problems. There is an emerging consensus in the research literature and amongst practitioners that improvements in mass transits, coupled with promotion of non-mechanized modes, can alleviate challenges in urban mobility, especially in big dense cities (Banister 2005, Cervero 1998, Dimitriou and Gakenheimer 2011).

Justification and Approach

There is a large body of research on mass transits, feeder bus planning as well as on non-mechanized modes like walking and cycling. However, there is paucity of research on how to plan all the last-mile modes together with the transit to generate synergy. There is an increasing realization that the accessibility of transit stations has a big impact on transit ridership, however there is not enough research focussed on measuring and improving it in different urban contexts. Further, there is limited research on demand estimation for cycling as a commuting option, especially for the last-mile trip to transit stations. This research tries to address these gaps.

Many renowned researchers highlight a gap between research and practice in the domain of urban transportation (Banister 2005, Cervero and Golub 2011). Being a complex issue, urban transportation has inter-linkages with various policy domains and quite often, theoretical research fails to capture the complexity of urban transportation, or is based on assumptions or models which do not work well in real cities.

In this research, we try to make our research more practice-oriented, first, by relying heavily on case studies using actual field data and surveys; and second by adopting a systems perspective in our research to deal with the complexity. We adopt a variety of methodological approaches and analytical tools like systems dynamics, data analytics, visualization and optimization, in our research depending on the requirements of the problem.

From literature reviews and discussion with other researchers, we have observed that the framing of the urban mobility problem varies, leading to differing, or even contradictory, conclusions when given the same facts. Hence, we define the problem of urban mobility from the perspective of policy makers whose concern is that traffic congestion and its associated costs may affect negatively a city's productivity and liveability through a multitude of urban dynamics including: (i) deterring companies from further investment in the city or, worse still, driving companies to move away, (ii) consuming too much of the residents' time, energy and resources in daily commuting to restrict time for leisure, skill upgrades or entrepreneurial activities, (iii) restricting employment opportunities due to long travel times and (iv) causing environmental pollution due to congestion, thus giving rise to serious health concerns for the city dwellers. The key measure we propose for this problem is the alleviation of any conditions that may discourage or impede the access of commuters to mass transit systems, especially during the morning peak hours as the congestion is more acute due to a smaller time-window vis-à-vis evening hours, besides additional school traffic. This will then be the focus of our research. An implied assumption is that if such impediments are removed, the urban mobility situation can be improved significantly.

Further, we adopt a modular approach in carrying out and presenting our research. Consequently, each chapter in this thesis has a self-contained literature survey and a set of conclusions related to the research questions that the chapter addresses. The overriding themes and conclusions of the thesis are finally woven together in the final chapter.

Brief Literature Survey

Global Challenges in Urban Mobility

Due to rapid urbanization and improved incomes, private motorization is increasing at a rapid pace, especially in the mega-cities of developing nations. The average speed of road vehicles has plummeted to less than 20 km/h in many big cities in India and China (Gakenheimer 2002, Pucher 2007). It deteriorates further during peak hours with average speeds down to less than 10 km/h in many instances (Pucher 2007, Tiwari 2011). In central Beijing, overall average motor vehicle speed fell from 45 km/h in 1994 to only 12 km/h in 2003, while average bus speed dropped from 17 km/h in 1994 to only 9 km/h in 2003. In central Shanghai, average speeds range from 9 to 18 km/h. During peak hours, more than half of the roads in Shanghai's central area are severely congested, and 20% of Beijing's inner roads are completely gridlocked, with a traffic speed of less than 5 km/h (Pucher 2007). The average speed of motor vehicles in Mumbai has plummeted from 38 km/h in 1962 to only 15-20 km/h in 2007 (Dimitriou and Gakenheimer 2011). In Chennai, and Kolkata, average speeds have dropped to less than 15 km/h (Pucher 2007).

Such traffic congestion becomes an economic issue when it reduces productivity and consequently takes a toll on the city's competitiveness in attracting new business. There are no reliable estimates of the economic costs of congestion in the developing countries, however, the cost of such congestion in the United States alone is estimated to have increased from $20 billion (2010 dollar value) in 1982 to more than $100 billion in 2010 (Bureau of Transportation Statistics 2011). In Europe, congestion has been estimated to cost approximately 2% of GDP, or a total of €120 billion (UITP 2003). The economic losses due to congestion in the developing world would be much higher, on a percentage basis, as the problem is more severe compared to the US or Europe.

From the environmental point of view, congestion increases automobile exhaust emissions causing air pollution, which contributes to major health problems. Concerns about the impact of urban transport on the quality of life and the environment are gaining importance (Mcclintock 2002, Krizek and Levinson 2005). Even in the developed cities with good mass transits and relatively lower population densities, there is increasing concern over how motorization and congestion degrade the quality of life and environment (Banister 2005, Midgley 2011).

Approaches to Improving Urban Mobility

Different cities have adopted different approaches to handle urban mobility issues. Most often, public policies focus on improvement of road infrastructure and public transport. Building new roads, flyovers, widening of existing roads is a common response. However, more road space leads to more private cars and there is hardly any impact on congestion in the long run, especially in big cities (Banister 2005, Cervero and Golub 2011). Few cities have successfully implemented transport demand management measures (TDM) like vehicle quota systems, congestion pricing and parking restrictions (Littman, Todd 2012), however, most cities find it politically difficult to implement restrictive TDMs. Improvement in public transport is also a pre-requisite for smooth implementation of TDMs to help reduce public resentment against these restrictive policies (Acharya 2005, Vuchic 2005). Some cities have experimented with various technology enabled initiatives to increase occupancy of private vehicles like high-occupancy vehicle (HOV) lanes and ride-sharing. However, these initiatives are often difficult to scale up and may have limited impact (Littman, Todd 2012).

In the long-run, development of efficient mass public transport along with promotion of non-mechanised modes like walking and cycling, is widely suggested as a sustainable solution to improve mobility in big cities (Dimitriou and Gakenheimer 2011, Vuchic 2005). However, to compete successfully with cars and motor-cycles, public transport must strive to provide a door-to-door service to commuters. But lack of good connectivity between home/office and mass transit stations may dissuade people from riding transits (Cervero 1998, Cheong and Toh 2010, Mohan 2008, Givoni and Rietveld 2007). The literature shows that ridership on many metro rail systems falls short of the projections made to justify them (Flyvbjerg, Buhl, et al. 2005, D. H. Pickrell 1992, Mohan 2008). Hence development of good last-mile feeder services and promotion of efficient short-distance modes like cycling for the last-mile, as well as a short-distance end-to-end option, are important for improving urban mobility.

Cycling can be an efficient solution for the last-mile. Apart from providing efficient last-mile connections, it can also support a significant share of end-to-end short-distance trips. It is a clean, cheap, fast and space efficient mode of transport for short-distance city trips (Dekoster and Schollaert 1999, Heinen 2011, Pucher and Buehler 2008). Hence, promotion of cycling for commuting can potentially reduce traffic congestion, parking space requirements and roadway costs in many cities (Mcclintock 2002, Heinen et al 2010). Research studies suggest that even weather is not a major deterrent for regular cycle commuters unless conditions are rather extreme, i.e. less than 4-5°C or more than 35°C (Heinen et al 2010, Nankervis 1999, Moreno Miranda and Nosal 2011). However, in most cities, there is a lack of emphasis and clarity on promoting cycling for commuting purposes (Heinen, Wee and Maat 2010, Krizek and Stonebraker 2010).

Effective integration of cycling with transit may increase the catchment area and ridership of transits. It can also improve the overall efficiency of public transport by reducing the need for feeder buses (Krizek and Stonebraker 2010, Martens 2004). Many commuters can also cut down their total travel times by cycling to transit stations rather than taking feeder buses (Ellison and Greaves 2011, Keijer and Rietveld 2000).

Hence, this research first focuses on developing an effective approach to promote commuter cycling in cities. Further, we suggest a comprehensive approach in which the last-mile access can be assessed and improved in different cities by appropriate combinations of different modes.

Research questions and thesis outline

As cycling is considered the cheapest and one of the most efficient non-walk mode for accessing transit stations, we begin with the evaluation of popular cycling related policies like bike-sharing and develop a framework to segment and implement policies to promote commuter cycling, especially for the last-mile. We frame three research questions: first, do bike-sharing projects help in promoting commuter cycling in the long-run? ; Second, should city governments invest public funds in bike-sharing projects? ; Third, how should city governments choose and prioritize cycling related policies?

To address these research questions (chapter 2), we take a systems perspective on the issue and first, develop a systems dynamics model to simulate long-term impact of bike-sharing projects on commuter cycling levels in a city; second, we develop a framework to choose and prioritize cycling related polices under constraints. Two peer-reviewed papers based on this work were published in the proceedings of two international conferences. The first one, related to a systems perspective on commuter cycling policies, got the Brian Mar best student paper award in the 23rd Annual international INCOSE conference. It can be accessed on-line at:

http://onlinelibrary.wiley.com/doi/10.1002/j.2334-5837.2013.tb03086.x/citedby.

The second paper related to bike-sharing projects was presented and published in the proceedings of the 30th International Conference of the System Dynamics Society. It can be accessed on-line at:

http://www.systemdynamics.org/conferences/2012/proceed/papers/P1306.pdf

Next, in chapter 3, we examine the potential of commuter cycling, especially its role as one of the means of improving last-mile access, by studying in detail the case of Singapore. There is a paucity of reliable cycling demand data in most cities. The demand estimation is mostly based on surveys which are costly to carry out and may still not give reliable numbers. There is not much research on estimating commuter cycling demand/potential using the existing transportation data without conducting expensive surveys. Hence, our research question was: How to use the existing public transport data to better approximate commuter cycling demand and to suggest efficient cycling related policies? In this work (chapter-3), we use the EZ-link (fare-card) data from Singapore to estimate the commuter cycling demand for the last-mile and end-to-end trips by carrying out a geo-spatial analysis of short-distance trips. Based on the demand pattern, we suggest cycling policies and also develop an optimization model to pick the best locations and portfolio of policies for a given budget. A research paper based on this work was published in the journal "Annals of Operations Research". This paper can be accessed on-line at:

http://link.springer.com/journal/10479/215/1/page/1

Further, we attempt to investigate in detail the impact of last-mile access on the ridership of transits. Hence, in chapter 4, we conduct a study of Delhi metro to obtain a better understanding of the factors that determine the attractiveness of the rail transit systems and identify some of the ways to increase the ridership by improving the last-mile access. As discussed above, the literature mentions last mile connectivity as a key factor impacting transit ridership. However, most of the research on last-mile access focuses on issues related to efficiency and level-of-service related for feeder buses, such as fleet sizing, vehicle routing and demand responsiveness (Cordeau and Laporte 2007, Blainey, Hickford and Preston 2012). There is also some literature on promotion of non-motorized modes like walking and cycling for the last-mile (Martens 2004, Krizek and Stonebraker 2010). However, the economics of different last-mile solutions and their suitability in different urban contexts, especially in the developing world, are not well researched. In this chapter, through a case study of Delhi, we study various aspects of the last-mile access and its impact on metro ridership. This research is unique in the sense that it presents data from an extensive commuter survey in Delhi and examines issues specific to the city. However, the observations should be applicable to other similar cities. A paper based on this work is under review with the journal **"Case studies on transport policy"**

Finally, in chapter 5, we develop indices to measure the state of last-mile access to transit stations and show their application through the case studies and comparisons between Singapore and Delhi.

To improve something, we must be able to measure it. Presently, there is no comprehensive method or index to measure the time taken and quality of last-mile access. Hence, our key research question was: How to measure the last-mile accessibility of transit stations in a comprehensive and easy to use manner? Walking, cycling and feeder services are three most efficient modes of last-mile access. Hence, in Chapter 5, we develop indices to measure walkability, bikeability and feeder bus/ shared para-transit access to transit stations and further develop composite index called the Last Mile Index (LMI) to measure the overall quality of last-mile access from the policy perspective. We collect the last-mile data from the catchments of metro stations from Singapore and Delhi to show application of these indices. We visualize the data using GIS maps to make it more useful for policy makers. We also demonstrate its use in policymaking through actual case studies. A research paper based broadly on this work is under preparation for the journal **"Transportation Research Part A: Policy and Practice".**

Finally, in Chapter 6, we sum up and discuss policy implications, validity of results and limitations of our research findings.

Chapter-2
A Systems Perspective to Cycling Policies, Bike-sharing and Last-mile Cycling

Cycling as a Transport Mode: Benefits and Limitations

Cycling offers many benefits to the problems in urban mobility. As a clean, cheap and efficient mode of transport for short-distance journeys, cycling can potentially reduce traffic congestion, parking space requirements and roadway costs (Burke and Bonham 2010, Dekoster and Schollaert 1999, Mcclintock 2002). By consuming considerably less non-renewable natural resources than motorized transport modes, it is one of the most sustainable and efficient transportation modes for trips of distance up to 5 km (Katia and Kagaya 2011, Midgley 2011).

Moreover, since the spatial efficiency of bicycles is close to that of buses in mixed traffic condition, cycling qualifies as a non-congesting mode (National Research Council 1996). By providing efficient last mile connectivity, it can also play a vital role in increasing public transit ridership (Banister 2005, Dekoster and Schollaert 1999, Katia and Kagaya 2012, Krizek and Stonebraker 2010, Heinen, Wee and Maat 2010, Rietveld 2000). Hence an increase in the use of bicycle as a commuting option can potentially alleviate peak-hour congestion in many cases.

On the other hand, cycling becomes difficult during adverse weather. Although commuters do cycle under different climatic conditions, extreme temperature and precipitation (Pucher, Buehler and Seinen 2011); data suggests a significant decline in cycle usage during severe cold (<5 °C) or when hot and humid (>28 °C and > 60% humidity) (Capital Bikeshare 2012, Heinen, Wee and Maat 2010).

While data also suggest that cycling decreases when gradient exceeds 4% (Midgley 2011) and may not be suitable for the elderly or the disabled; pedelecs[1] may change the situation (Midgley 2011, OBIS 2011). Furthermore, there are surprising data from Netherlands and Germany that elderly people may not cycle less (Buehler and Pucher 2010, Pucher and Buehler 2008).

Finally, cycling safety is a big concern and often a major determinant of cycling modal share as cyclists are more prone to accidents in mixed traffic conditions (Pucher and Dijkstra 2000). Counter-intuitively, as the number of cyclists goes up, fatality rate as well as per capita cycling accidents can go down (Pucher and Buehler 2008).

Cycling in Urban Mobility: Trends and Policies

There are wide variations in the cycling modal share across cities as shown in **Figure 1**. The share of cycling has decreased substantially over the past three decades from a very high level in Chinese cities such as Beijing and Guangzhou. Such a decline is also observed in the Indian cities. This similarity in trend across both populous developing countries may be attributed to a combination of increased motorization, mass transport development, decline in cycling safety, and lengthening of trips due to city expansion (Tiwari 2011, Pucher 2007).

[1] Pedelec is a popular term for pedal assisted e-bike, as opposed to other types of e-bikes which do not require pedalling and are more similar to motorbikes. Regulations for these e-bikes are still evolving in most countries.

In the developed world, the level of cycling has been low and had declined further. However, cities such as Amsterdam and Tokyo are exceptions and have attained a fairly high cycling modal share (**Figure 1**) through a well-coordinated focus on cycling infrastructure and other cycle friendly policies.

Cycling can encourage a modal shift from private car to public transport by providing efficient last mile connections, leading to a reduction in road congestion due to the volume of cars. Such high usage of cycles for last mile connectivity has been observed in Japanese and German cities; for example, around 20% of transit users use cycling as a last mile mode in Tokyo (Katia and Kagaya 2011), enabled by an extensive bicycle parking infrastructure at the transit stations (Pucher and Buehler 2008, Katia and Kagaya 2011).

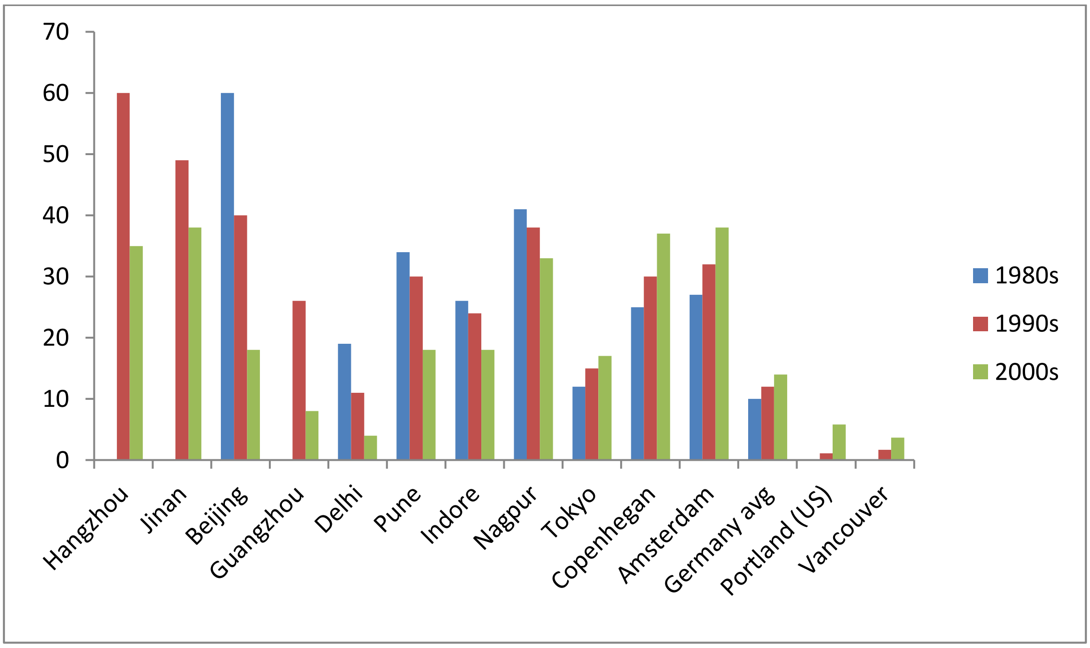


Figure 1 Cycle Modal Share across Cities

Sources : (Tiwari and Jain 2008, Pucher and Buehler 2008, Pucher 2007, Pucher, Buehler and Seinen 2011, Pan 2011, Katia and Kagaya 2011). *Note that: (i) values may not be comparable across cities due to differences in data collection methodologies and definitions, (ii) the 1980s data are not available for some cities.*

Cycling is an efficient option for end-to-end short-distance trips. It can have a large modal share of total trips especially in small to medium sized cities with mixed land use (National Research Council 1996, Mcclintock 2002, Pucher and Buehler 2008). However, while most cities acknowledge the benefits of cycling, they have yet to develop clear strategies to encourage it. Instead, most governments focus on improving public transport services, traffic flows, or road infrastructure to deal with peak traffic while cycling hardly gets any attention (Barter 2008, Pucher 2007, Pucher, Dill and Handy 2010, Tiwari and Jain 2008).

There is also a lack of clarity on how to plan for cycling: should cyclists share roads with motorized traffic, or with pedestrians, or to have dedicated paths (Heinen 2011, Mcclintock 2002, Pucher, Dill and Handy 2010, Rietveld 2001). Often, policies intended to promote cycling in general end up benefitting recreational cycling and not commuter cycling (Heinen 2011, Buehler and Pucher 2012). There is also an apprehension among policy-makers that cycling infrastructure may worsen the overall traffic situation by eating into the limited road-space (Barter 2008, Pucher, Dill and Handy 2010, Tiwari 2011).

Nevertheless, many cities, especially in Europe, have tried to promote cycling using different policies, particularly through the implementation of bike-sharing projects. The world over, there has been a significant growth in the number of cycle related interventions especially in the bike sharing systems (Burke and Bonham 2010, Martens 2004, Midgely 2009, Shaheen, Zhang, et al. 2011).

Bike-sharing: Evolution, Characteristics and Present Status

A bike-sharing system is a short-term rental scheme allowing bicycles to be collected and returned at any one of several self-serve stations. It enables commuters to flexibly use bicycles without incurring the cost and trouble of owning and maintaining them (Shaheen, Guzman and Zhang 2010).

Bike-sharing systems give cycling characteristics of public transport including (i) network of stations, (ii) pay as you use, and (iii) ease to incentivize by the city government (OBIS 2011). It shows ‘Mobility on demand’ features when station density and cycle availability are high. Bike-sharing may help in efficient use of resources by facilitating quick turn-around of cycles and parking spaces (Midgley 2011).

While bike-sharing systems have evolved over the past 45 years (DeMaio 2003, DeMaio 2004, Midgely 2009) (**Figure 2**), they came to prominence in 2007 with the launch of *Vélib*, a third generation bike-sharing program, in Paris. Starting with around 7,000 bikes, the program has expanded to more than 20,000 bikes to date. This massive program and its apparent operational success redefined the expectations of bike-sharing systems and led to enormous global interest.

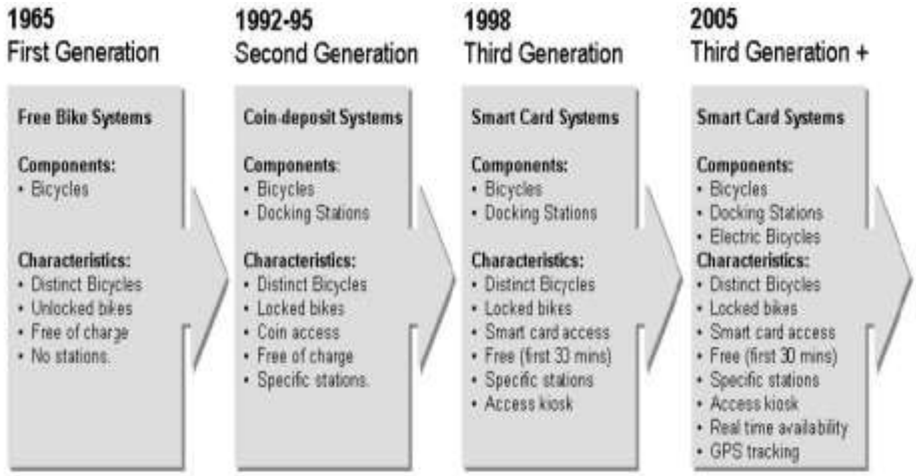


Figure 2 Evolution of Bike-sharing Systems

(Source : Midgely, 2011)

The number of bike-sharing schemes has grown significantly over the past decade, reaching a figure of 375[2] programs in 33 countries by May 2011, as shown in **Figure 3** (Midgley 2011). This is accompanied by an impressive growth in bicycle fleet size - this phenomenal rate of growth in bicycle-sharing schemes and fleets has exceeded growth in every other form of urban transport (Midgley 2011).

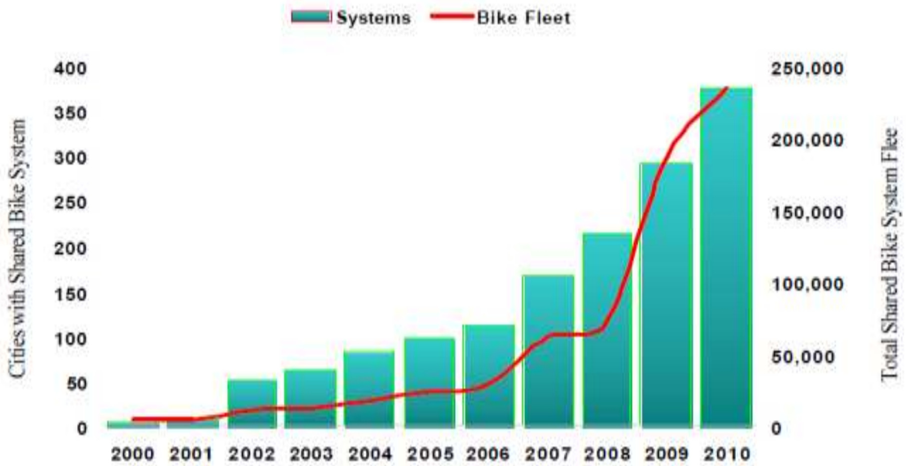


Figure 3 Growth in Bike-sharing Systems and Fleet

(source : Midgley, 2011)

[2] Including smaller pilot studies

This apparent success of bike-sharing projects comes with its challenges. Because of uneven travel demands, re-distribution of bikes using trucks is often necessary. This is not just a problem of cost, but may affect the availability in stations with high demand (Shaheen, Guzman and Zhang 2010, Midgley 2011). Some projects have experimented with pricing and incentives to reduce re-distribution (Velib 2012), which has met moderate success.

Moreover, while reducing congestion through encouraging modal shift from cars to bikes is often one of the key objectives, most bike-share trips may substitute walking or public transport instead, resulting in limited impact on congestion (Midgley 2011).

Furthermore, while total cycle trips may have grown quickly after introduction of bike-sharing in many cities, the overall cycle modal share in these cities can still be low. Besides making cycling more acceptable and trendy (Midgely 2009), bike-sharing can bring in many new but occasional cyclists. While a larger number of cyclists may lead to better cycling infrastructure (OBIS 2011), it is unclear whether bike-sharing will make cycling a significant mode in urban mobility in the long-term.

Finally, data shows that most of the big bike-share programs are, in whole or in part, supported financially by local authorities (Midgely 2009, Midgley 2011). Such support can either be direct or indirect through the sale of advertising rights, for example. To date, none of the programs can be considered a financial success (Midgley 2011) although, given the recent implementations, it may be premature to assess the long-term viability of their business models. In Hangzhou, for instance, the local authority is promoting public transit ridership by financing explicitly an almost free bike-share service (Shaheen, Zhang, et al. 2011).

Given this backdrop, it is clear that the sustainability and long-term effectiveness of bike-sharing systems is a concern; a better understanding of their long-term impact on cycling and the urban mobility problem is necessary. Besides, we need to develop a general framework to identify and prioritise the most effective, cost-effective and easy to implement cycling related policies in a city.

Problem Definition and Perspective

For cycling to play a part in alleviating the urban mobility problem, it must attain significant modal share during the morning peak-hour. Hence, all cycling related policies, including the bike-sharing projects, should be evaluated based on their effectiveness in attracting the morning peak-hour commuters. The commuters will compare cycling with the other available modes of transport over a range of factors like safety, affordability and comfort**.** Moreover, the relative importance of these factors can be influenced by a city's attributes.

Why systems perspective is necessary in this issue?

To best promote commuter cycling as a last-mile alternative, or as an end-to-end solution, to address urban mobility challenges, how cycling related policies fit in with other transport policies, as well as with urban planning and environmental policies, has to be understood. A systems perspective is required to study this issue, considering its complexity (Meadows 2008).

Taking a systems perspective allows us to reconcile multiple objectives, competing solutions, different urban contexts and diverse stakeholders in urban mobility; while a reductionist approach to policymaking may lead to unintended consequences, counterproductive results and even new problems for the system.

In this chapter, first, we take a systems perspective to understand and evaluate the long-term impact of bike-sharing projects on the modal share of cycling. We use causal loops and a systems dynamics based model for this purpose. We focus on commuter cycling during morning peak-hours in the urban environment when commuters are going to work; an implied assumption is that if the morning peak-hour traffic can be alleviated, the problems of urban mobility can be mitigated to a large extent in many cities. We believe that commuter cycling can play an important role in improving peak-hour mobility by reducing the number of cars and motor-bikes on roads, in addition to providing increased access to mass transits.

Second, we try to understand the linkages of commuter cycling with a range of policies in the related domains and then suggest an implementation framework to make policies more effective. The systems perspective enables numerous policies to be better prioritised and co-ordinated.

Methodology

First, we understand the unique features and requirements of commuter cycling in general and last-mile cycling in particular. This understanding lays the foundation for further policy analysis. We also argue how certain factors may or may not affect the potential of commuter cycling in a city.

Second, we not only figure out the policies related to commuter cycling, but also understand their inter-linkages within the urban mobility system and beyond by identifying important causal/feedback loops. The objective is to improve performance of the system as a whole robustly rather than optimizing performance of a part.

Third, based on the existing theoretical and empirical research findings, we develop causal loops and a systems dynamics based model to evaluate long-term effectiveness of bike-sharing projects in improving modal share of cycling in commuting.

Fourth, as a complex system involves myriad policy decisions, we apply the Pareto principle to identify the most effective policies requiring minimal resources and effort to promote commuter cycling.

Fifth, we translate the systems perspective into a practical implementation framework by addressing policy-makers' common concerns/constraints related to financial, political and technical viability. We don't intend to be comprehensive in our analysis of policies, rather the emphasis is on the demonstration of a methodology that imbibes systems thinking into policymaking.

The Nature, Potential and Policies for Commuter Cycling

Types of cycling

To make effective, well-co-ordinated policies to promote commuter cycling, it is important to understand the nature and potential of commuter cycling in a city. Commuters may make the complete trip by cycle (end-to-end cycling) or may use cycling for the first or last-mile access in combination with mass transit: i.e. to access the transit station from home and vice-versa (home-end) or transit station to work-place and vice-versa (work-end) (Figure 4).

All these are distinct forms of commuter cycling with specific policy requirements. First-mile (home-end) trips need existence of a good mass transit as a pre-requisite and require safe cycling infrastructure mainly around suburban transit stations, apart from parking facilities at stations (Brunsing 1997, Krizek and Stonebraker 2010, Martens 2004). Last-mile (work-end) trips are found to be small in number compared to first-mile (home-end) trips as transit network density is normally high in the business districts (Rietveld 2000, Martens 2004). End-to-end cycling to work requires trips to be short (preferably less than 5km). Cycling infrastructure along the key origin-destination (O-D) flows and parking facilities at the workplaces are also required (Buehler and Pucher 2012, Heinen, Wee and Maat 2010). Cycling to school (especially primary and high schools) is further constrained as it needs specific cycling safety infrastructure and training/promotion in schools (Buehler and Pucher 2010, Moritz 1997).

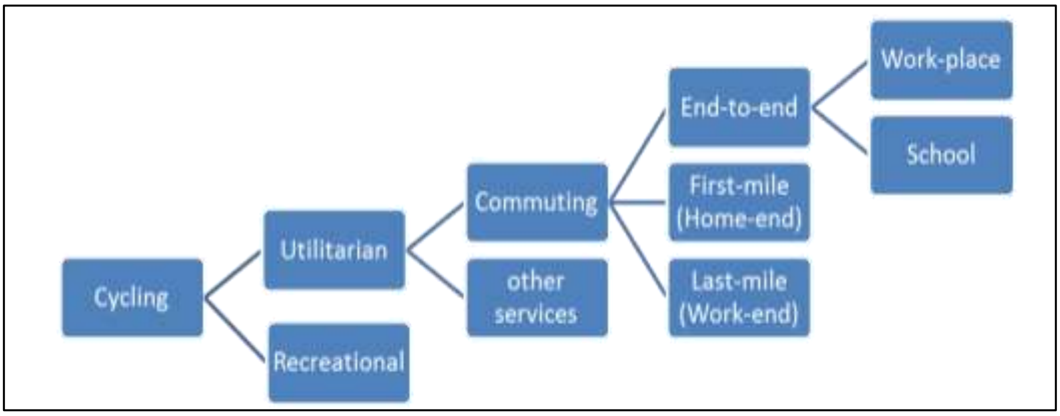


Figure 4 Types of Cycling

Challenges and potential

Safety, comfort, convenience and acceptability of cycle as a mainstream transport mode are the important determinants of commuter cycling. Nevertheless public policies can address and improve many of these factors (Pucher and Buehler 2008, Barter 2008). For longer trips cycling becomes uncomfortable and inefficient. Hence short trip length is a major pre-requisite to encourage commuters to cycle (Ellison and Greaves 2011, Heinen, Wee and Maat 2010, Brunsing 1997).

Aligning Policies with Objectives

Research shows that effective integration of cycling with transit can increase the catchment area and ridership of transits. It can help in curtailing public expenditure on feeder buses as more commuters switch to cycling (Krizek and Stonebraker 2010). Many commuters can cut down their total travel times by cycling to fast transit stations rather than taking feeder buses (Ellison and Greaves 2011, Keijer and Rietveld 2000). There are no major natural constraints to commuter cycling and public policies can encourage commuters to cycle if the trip lengths are short, not more than 5km, preferably up to 3 km especially for the last-mile (home/office to transit station) connections (Heinen, Wee and Maat 2010, Keijer and Rietveld 2000, Koh, et al. 2011). These short-distance trips could either be the last-mile trips as a part of a public transit journey or could be end-to-end trips. It is also useful to have an idea of spatial distribution of these trips using traffic flow data. For example, feeder bus data may be used to estimate the potential of first/last-mile cycle trips in the neighbourhood of a mass transit station.

From a commuter's perspective, safety plays a key role in making cycling a mainstream commuting mode in an urban mixed-traffic environment. As the level of safety improves, more commuters will choose to cycle. Furthermore, motorists develop better awareness of cyclists when there are more of the latter on the roads, leading to improved cycling safety, resulting in a reinforcing loop R1 as shown in **Figure 5**. Such a dynamic feedback loop has been observed in numerous research studies (Mcclintock 2002, Pucher and Buehler 2008, Pucher, Dill and Handy 2010, Jacobsen 2003).

Therefore, policies and infrastructure promoting cycling safety are found to be effective in promoting cycling. Such policies include (i) provision of cycle lanes along busy corridors, preferably separated from motorised vehicles, (ii) cycle-friendly intersections and (iii) wide-spread traffic calming. Integrity of cycling networks becomes more important for commuter cycling than the nature of the network (shared cycle lane on road or separated cycle track).

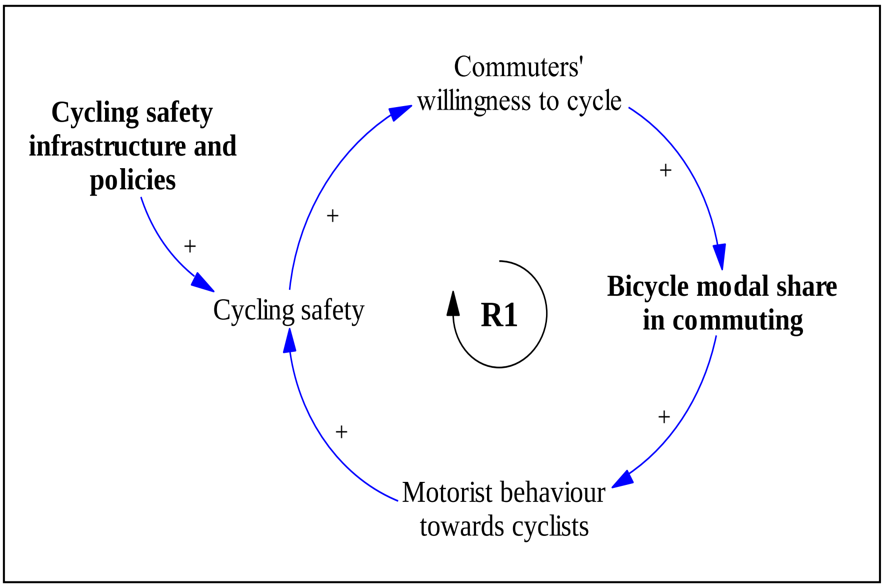


Figure 5 Safety in Numbers

Besides cycling safety, extensive cycle parking, especially at transit station, and mixed land-use can also increase cycling levels (Heinen, Wee and Maat 2010, Keijer and Rietveld 2000, Pucher, Dill and Handy 2010). Good bicycle parking at transit stations have been shown to encourage the usage of bike as a first mile (especially home-end) transportation mode (Brunsing 1997, Katia and Kagaya 2011, Keijer and Rietveld 2000, Krizek and Stonebraker 2010). Mixed land-use in urban planning policies puts the workplace closer to the home, thereby decreases the average trip length and enhances the attractiveness of cycling as an option for end-to-end trips.

The contribution of these measures, besides others, is shown through various causal linkages in **Figure 6**. The balancing loop B1 in the figure illustrates the dynamics when cars are substituted by bicycles and/or mass transits, and vice versa. Better public transport and car discouragement policies, such as higher tax for car usage/ownership, high parking charges, no car zones and fuel taxes, would further encourage the switch from private car to bicycle. **Figure 6** is not a comprehensive explanation of urban mobility dynamics, rather it is just an illustration of the inter-linkages of commuter cycling related policies.

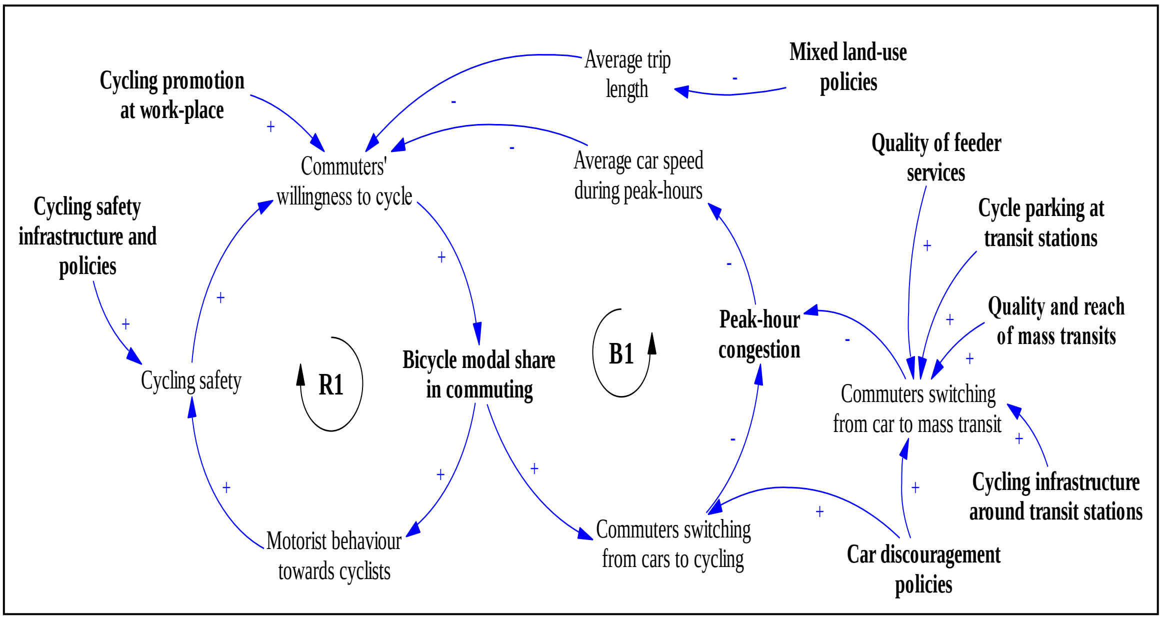


Figure 6 Causal Feedback Loops Depicting Congestion and Cycling Related Policies

There is often confusion between policies for commuter cycling and 'cycling in general'. The policies to promote cycling in general, may not always help in commuter cycling (**Figure 7**). A typical example of such policy is bike-sharing projects. Bike-sharing systems are unlikely to have a big impact on commuter cycling levels as the cost of owning and maintaining a bicycle is not the key issue preventing the choice of cycling in urban peak-hour commute. Besides, a majority of the commuters also follow the same origin-destination travel routine, thereby minimizing the need to rely on a large geographical coverage of bike-sharing network (Midgely 2009, OBIS 2011, Shaheen, Guzman and Zhang 2010).

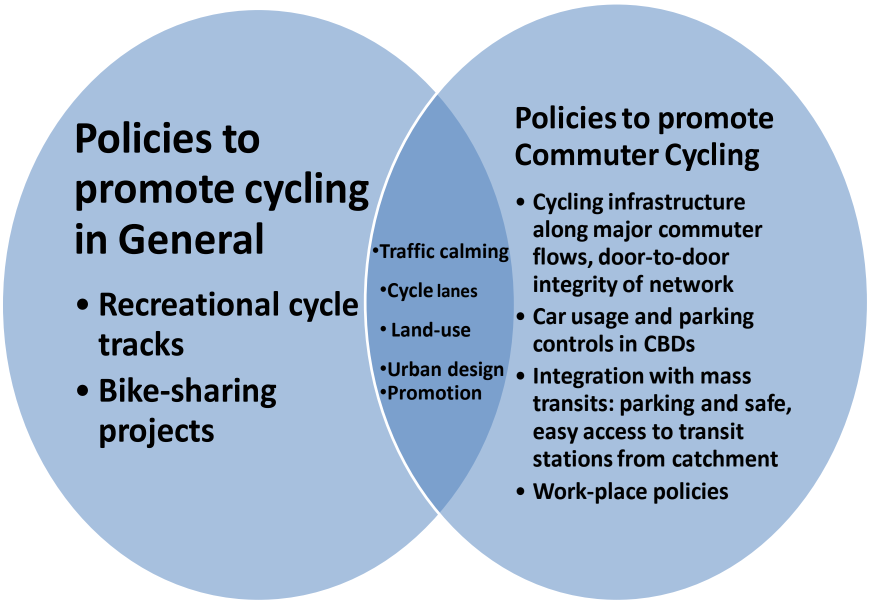


Figure 7 Distinction between Policies Commuter Cycling and Cycling in General

Cycling and Bike-sharing: Taking the Systems Perspective

As shown in **Figure 5**, safety[3] plays a key role in making cycling a credible choice as a transport mode in an urban mixed-traffic environment. As the level of safety improves, more commuters will choose to cycle. Furthermore, motorists will develop better awareness of cyclists when there are more of the latter on the roads, leading to improved cycling safety, resulting in a reinforcing loop R1 as shown in **Figure 5**.

Besides cycling safety, extensive cycle parking, especially at transit station, and mixed land-use can also increase cycling levels (Krizek and Levinson 2005) (Buehler and Pucher, Cycling to Sustainability in Amsterdam 2010)

[3] Cycling safety excludes compulsory use of helmets. There is research showing that compulsory helmet laws may be a hindrance in growth of cycling (Pucher, Dill and Handy 2010) due to a negative perception of cycling safety.

(Mcclintock 2002) (Pucher and Buehler 2008) (Pucher, Dill and Handy 2010). Good bicycle parking at transit stations have been shown to encourage the usage of bike as a last mile transportation mode (Pucher and Buehler 2008, Katia and Kagaya 2011). Mixed land-use in urban planning policies put the workplace closer to the home, thereby decreases the average trip length and enhances the attractiveness of cycling as an option. The contribution of these measures to the reinforcing loop R1 is shown in **Figure 8**. The balancing loop B1 in **Figure 8** illustrates the dynamics when car are substituted by bicycles, and vice versa. Better public transport and car discouragement policies, such as a higher tax for car usage and ownership, would further encourage the switch from private car to bicycle usage.

On their own, bike-sharing systems are unlikely to have a big impact on cycling levels as the cost of owning and maintaining a bicycle is not the key issue preventing the choice of cycling in urban peak-hour commute. A majority of the commuters also follow the same origin-destination travel routine, thereby minimizing the need to rely on a large geographical coverage of bike-sharing network. Instead, cycling safety, comfort and trip length are the key determinants of cycling modal share, and bike-sharing does not change much of these attributes.

Data from big bike-sharing projects, including *Velib*, *Bixi,* and *CaBi*, shows that while the number of cycling trips has increased in Paris, Montreal, and Washington DC respectively, the modal share remains low and accounts for less than 2% of all trips. On the other hand, cities in Netherlands, Denmark, Germany and Japan continue to have high levels of cycling modal share without any big bike-sharing system (Katia and Kagaya 2011, Buehler and

Pucher, Cycling to Sustainability in Amsterdam 2010, Warren 2010). Essentially, if cycling is already an attractive commuting option due to safety, comfort and trip length considerations, there are few factors prohibiting an individual from owning using his/her own bike.

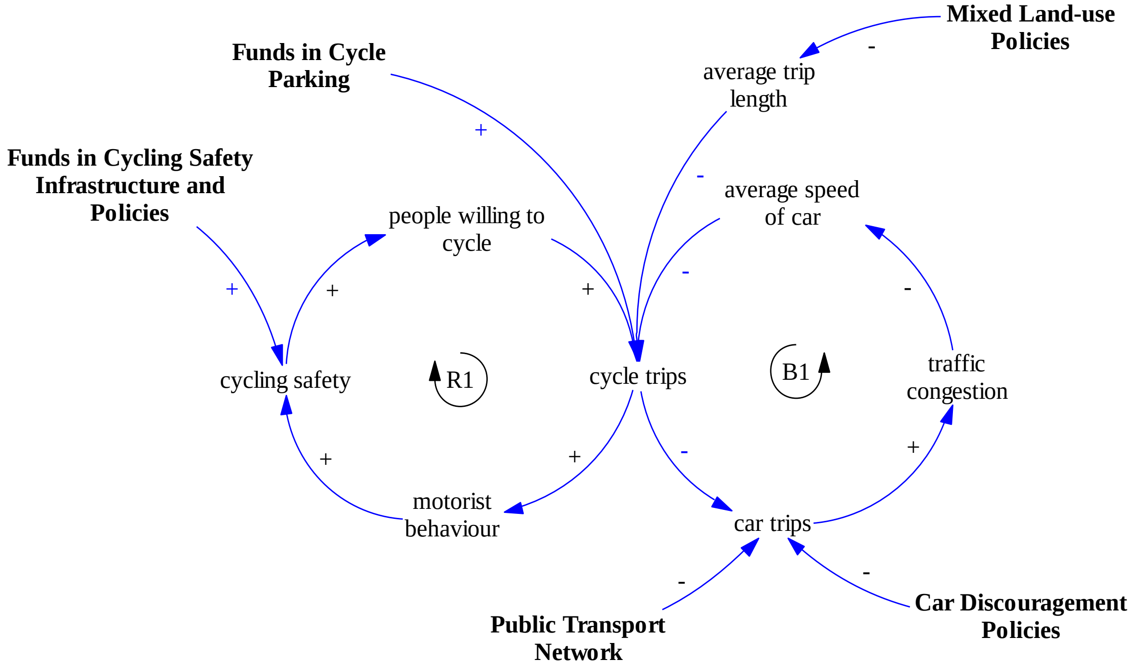


Figure 8 Causal Loops View of Cycling Levels in Cities

It is also important to ensure that bike-sharing systems are not implemented at the expense of private cyclists, since they are competing for the same parking spaces. If a significant portion of shared bike rides come from private commuter bike-rides (Midgley 2011), there would be little improvement in the cycling modal share.

Nevertheless, bike-sharing systems may increase the total number of cyclists on the road and a corresponding demand for better cycling infrastructure. This may in turn prompt governments to increase fund allocation for cycling (OBIS 2011). This dynamic is captured in the reinforcing loop R2 in **Figure 9**. Bike-sharing may also improve public transport ridership as some of the shared bike trips would be last-mile trips[4].

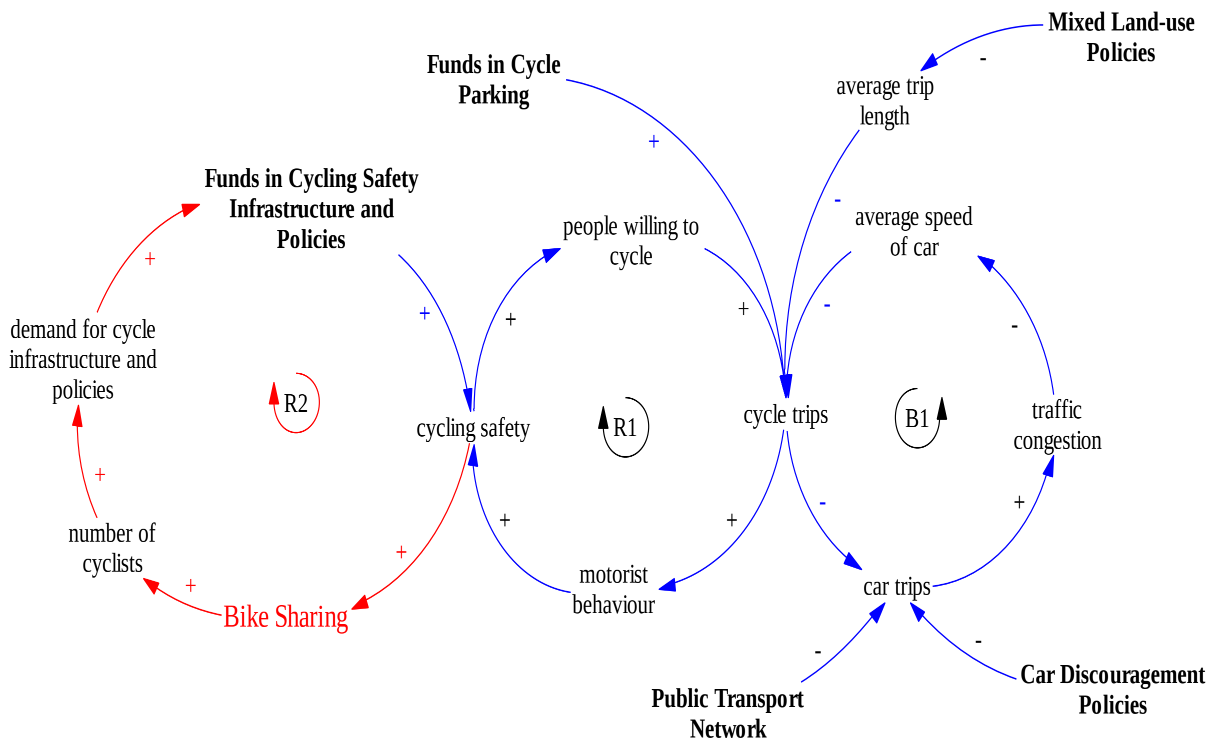


Figure 9 Short-term Impact of Bike-sharing

As highlighted earlier, most big bike-share programs have not shown to be economically sustainable (Midgely 2009, Midgley 2011). In the long-run, continued support of these bike-sharing projects using public funds may reduce the resources available to improve and maintain the cycling safety and parking infrastructure. This dynamics is shown by time delayed relationships in the balancing loop B2 in **Figure 10**. Conversely, if only private capital is invested in bike-sharing projects, city governments can deploy the funds saved to focus on cycling safety and parking infrastructure.

[4] Assuming that last-mile cycle trips exceed the transit trips substituted by cycling

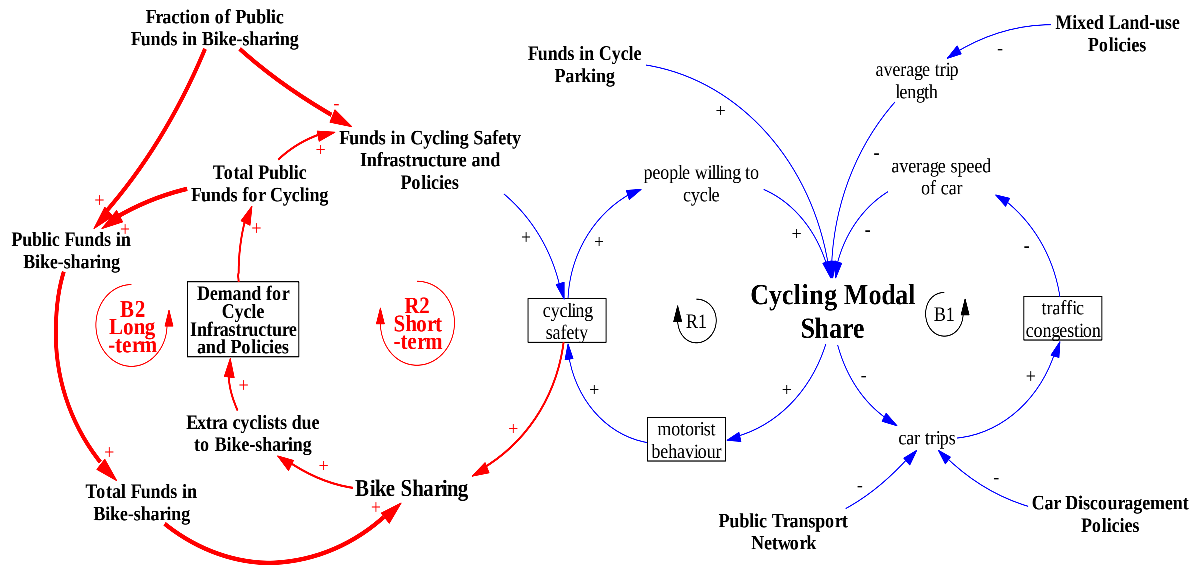


Figure 10 Long-term Implications of Bike-sharing Systems

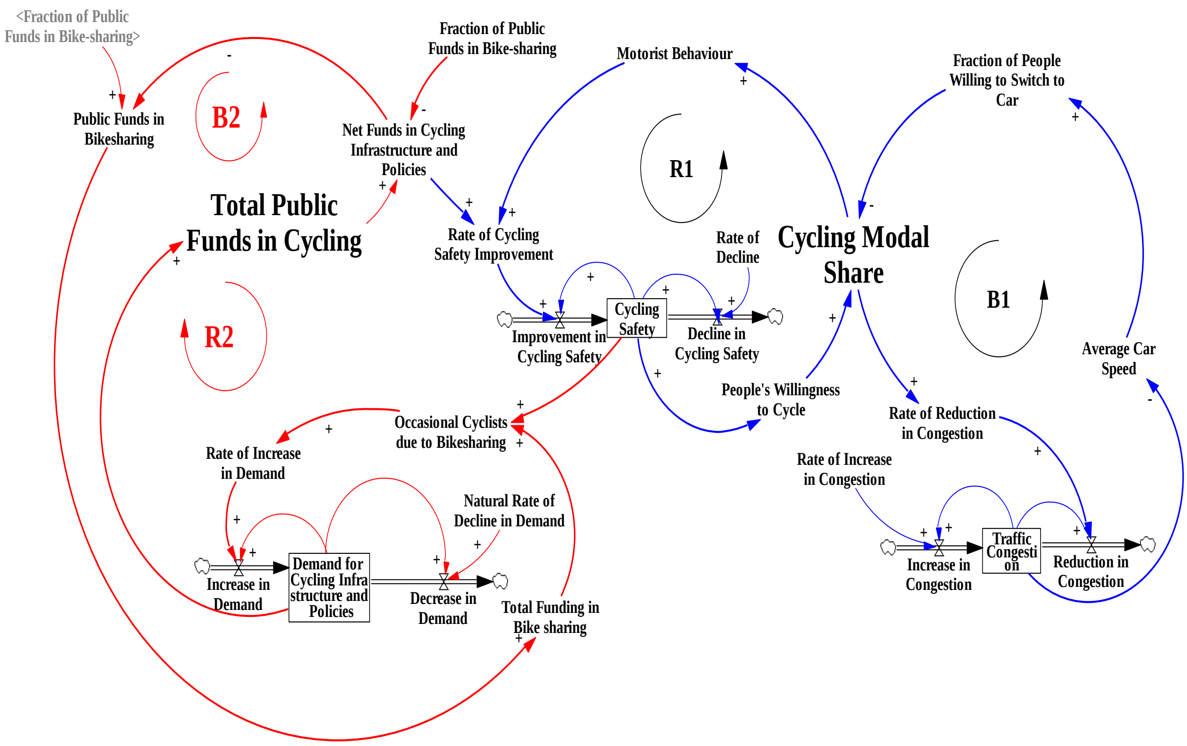


Figure 11 SD Model Simulating Long-term Effect of Bike-sharing Systems

Further, I develop a Systems Dynamics (SD) based model that tries to capture the complexity of the cause-effect relationships through various reinforcing and balancing loops (Appendix 'A' for details)

Model Description

Figure 11 shows the SD model that tries to simulate long-term effect of public funding in bike-sharing systems on the overall cycling modal share. It assumes relationships as observed in actual projects and/or as indicated in research literature (Buehler and Pucher 2010, Conway 2012, Heinen, Wee and Maat 2010, Jacobsen 2003, Krizek, Barnes and Thompson 2009, Shaheen, Guzman and Zhang 2010). Vensim PLE software is used to develop and simulate this model.

It may be pointed out that unlike forecasting models, the value of this SD model lies primarily in illustrating the likely direction of change in the monitored outcome (cycling modal share) in the long-term due to a certain policy intervention (public investment in bike-sharing). This model tries to capture the interplay of a variety of variables which may apparently have no direct linkage with the outcome.

The variables in this model are classified as stock or flow variables. The stock variables capture the level at different points of time while the flow variables show the rate of change. For example, Cycling safety, traffic congestion and cycling modal share are the stock variables; while rate of increase in congestion, rate of cycling safety improvement and rate of increase in demand for cycling are flow variables. There are some dimensionless variables like cycling safety, traffic congestion and demand for cycling infrastructure, which are assumed to be continuous variables with value ranging from 0 to 1. For variables related to funding, million $ / 10,000 population per annum is used as a unit and its range is assumed to be from 0 to 1. Km/hour is taken as the unit of average car speed (intra-city) with a range of 0 to 80 while all rate variables are expressed as percentage change per unit of time.

The mathematical relationships between different variables within the model are simply indicative based on causative inferences drawn from the literature as referred below each figure (Fig 12-16). The input-output functions for all sub-systems in this model are assumed to be monotonically increasing or decreasing (as indicated by the polarity sign + or - on the respective arrow in the model) continuous functions. I use look-up function in Vensim software to graphically create these functions in this model. Four key relationships (cycling safety versus cycling modal share; average car speed versus cycling modal share; funds in cycling infrastructure versus cycling safety and number of cyclists (including occasional cyclists) and demand for cycling infrastructure) that determine the net effect of reinforcing (R1 and R2) and balancing (B1 and B2) loops are assumed as shown in Figure 12 to Figure 15. Key references suggesting these figures are mentioned below the respective figure.

Figure 12 Cycling Safety and Modal Share

sources: (Heinen 2011, Dekoster and Schollaert 1999, Mcclintock 2002)

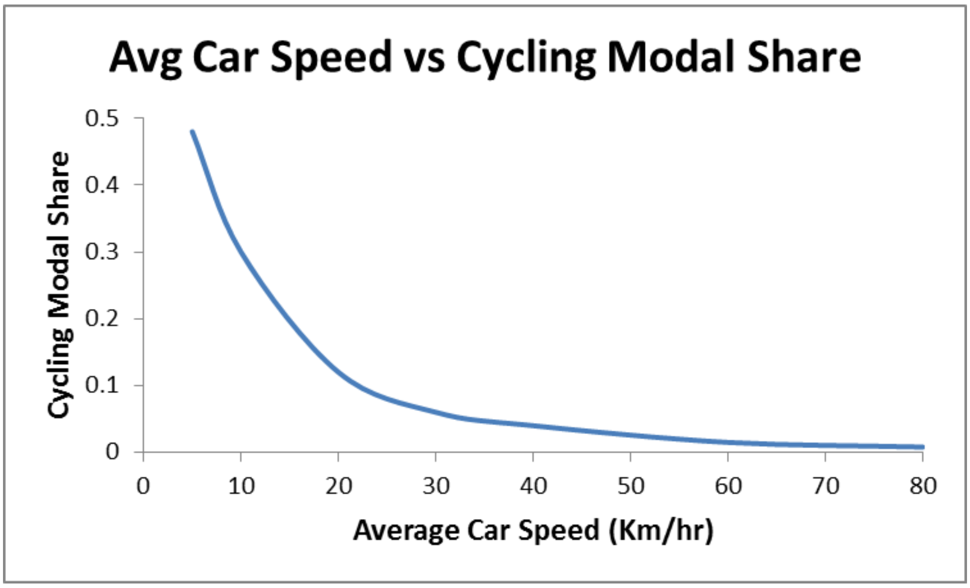


Figure 13 Average Car Speed and Cycling Modal Share

sources: (Buehler and Pucher 2010, Tiwari and Jain 2008, Ellison and Greaves 2011, Heinen, Wee and Maat 2010)

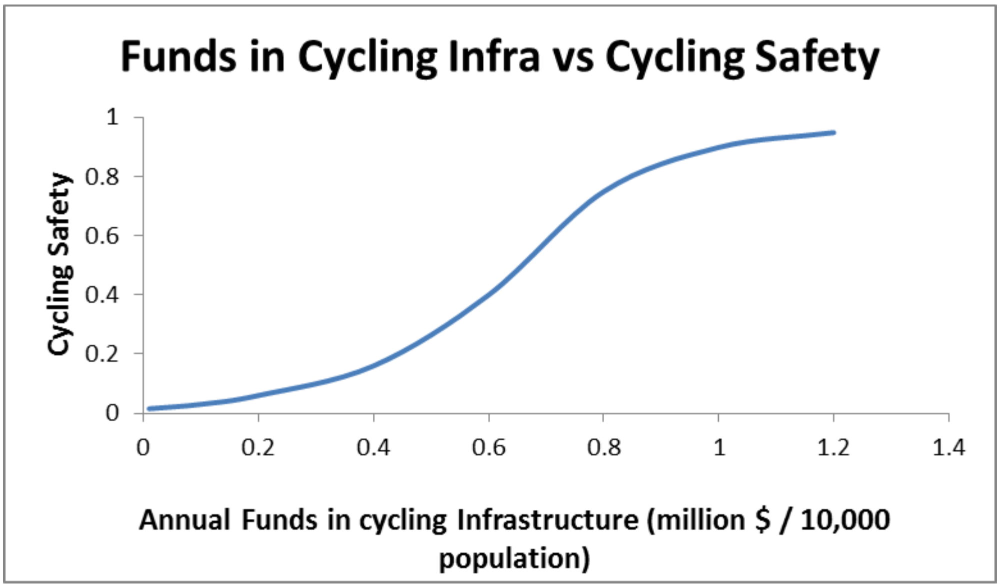


Figure 14 Cycling Infrastructure Funding and Safety

Sources: (Buehler and Pucher 2012, Buehler and Pucher 2010, Conway 2012)

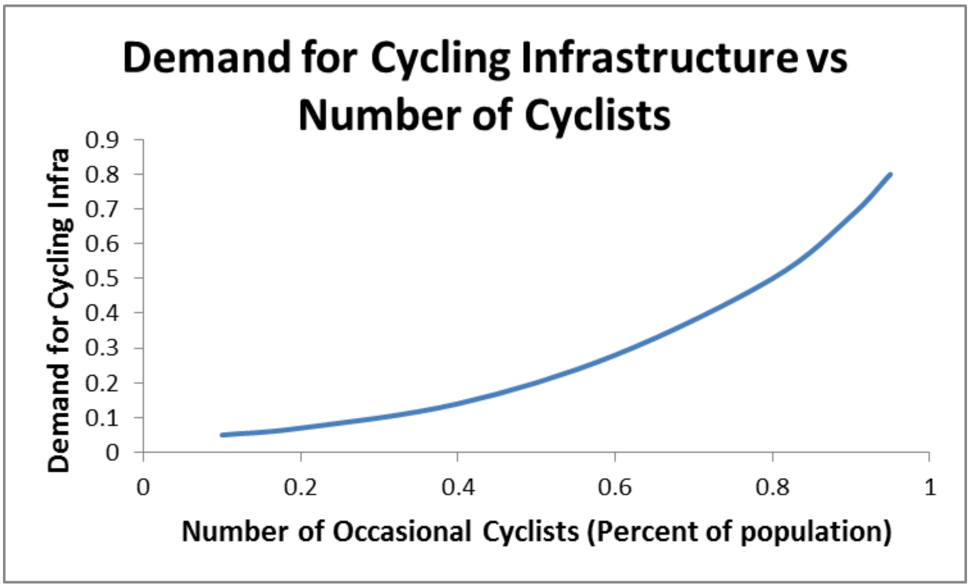


Figure 15 Number of Cyclists and Demand for Infrastructure

Sources: (Conway 2012, Jacobsen 2003, Krizek and Stonebraker, Bicycling and Transit: A marriage unrealized 2010)

Key Simplifying Assumptions

- Public funds are limited. Expenditure in bike-sharing systems would reduce funds available for cycling infrastructure.
- Commuters' willingness to cycle depends mainly on the actual as well as perceived safety of cyclists
- Once started, It is difficult to shut down loss-making bike-sharing systems in public domain

Simulation Results

Various simulations are run for different scenarios with this SD model. These scenarios include different levels (share of total public funds) of public funding in bike-sharing in different city types (low and high cycling modal share). The base case in these simulations assumes that no public funds are invested in bike-sharing projects. Model outputs are plotted for the cycling modal share and the future funding requirement for different city types for a time horizon of 10 years. These graphs are depicted in **Figure 16** to **Figure 19** *(with a common legend as shown below* **Figure 16***)*. The results suggest that with diversion of cycling- related public funds to bike-sharing, cycling modal share rises in the short run, but in the long-run registers a marginal decline as more public funds are invested to sustain bike-sharing projects at the cost of cycling infrastructure. This trend is observed for cities with low as well as high cycling levels. Further, a comparison of the base case with the other cases (1, 2 and 3) in these simulations shows that if additional public funds are invested in cycling infrastructure instead of bike-sharing projects, cycling modal share is likely to grow more in the long-run.

For a city with low initial cycling modal share

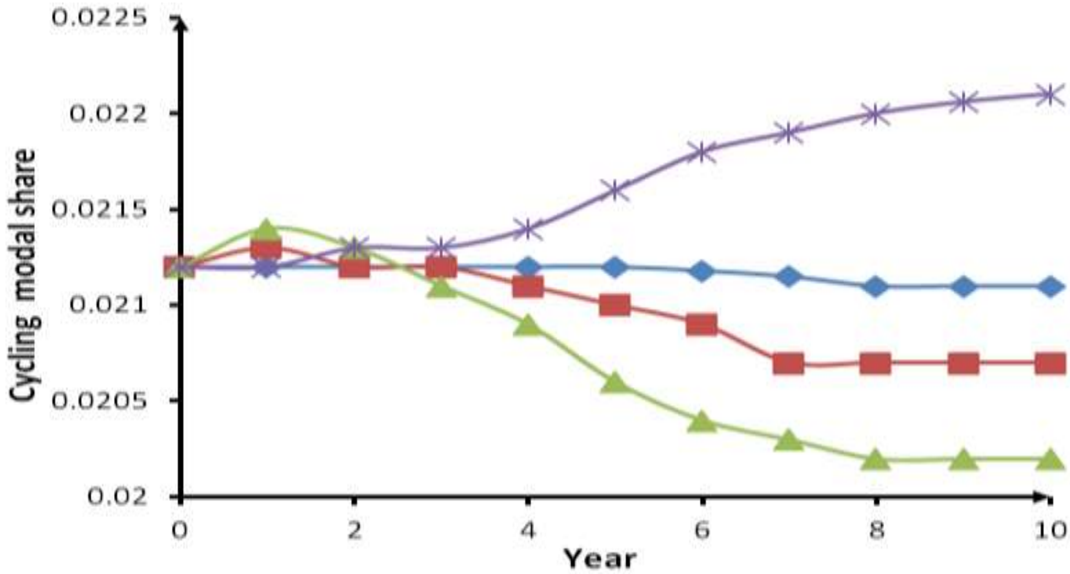
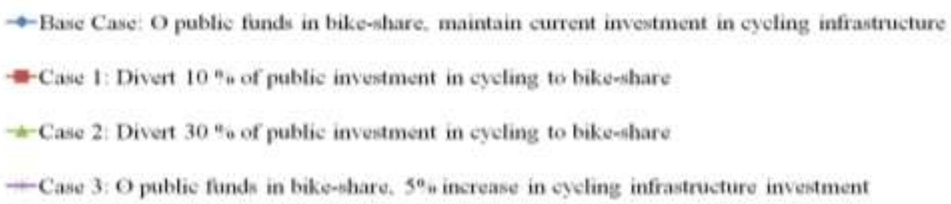


Figure 16 SD Model Result: Cycling Modal Share for a City with Low Initial Cycling Level



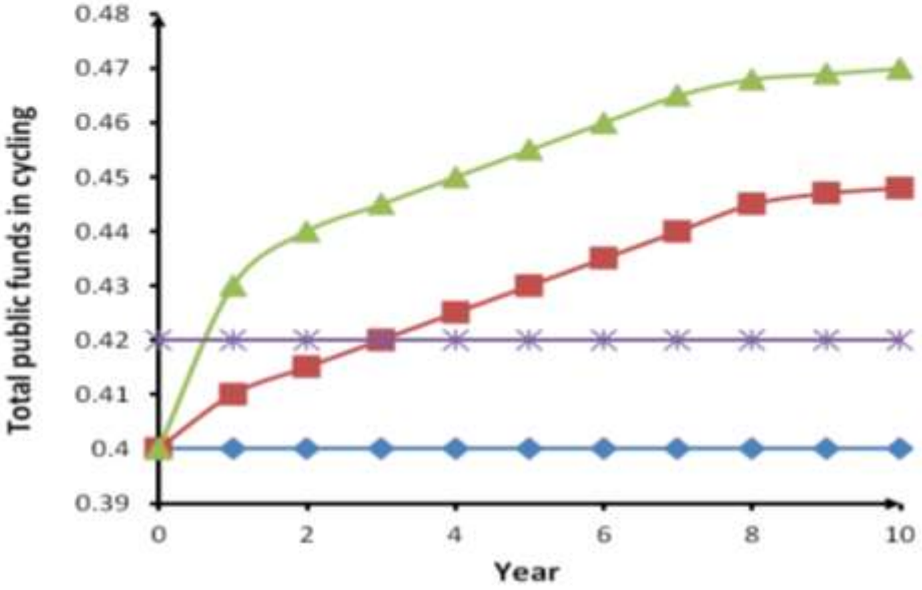


Figure 17 SD Model Result: Public Funding Levels for a City with Low Initial Cycling Level (Annual expenditure in million$ per 10,000 population)

For a city with high initial cycling modal share:

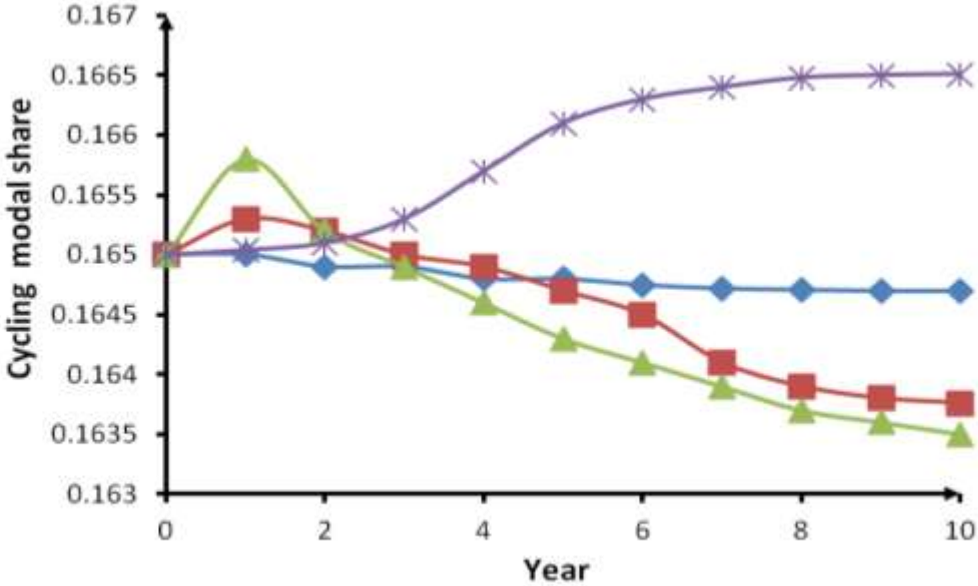


Figure 18 SD Model Result: Cycle Modal Share for a city with high Initial Cycling Level

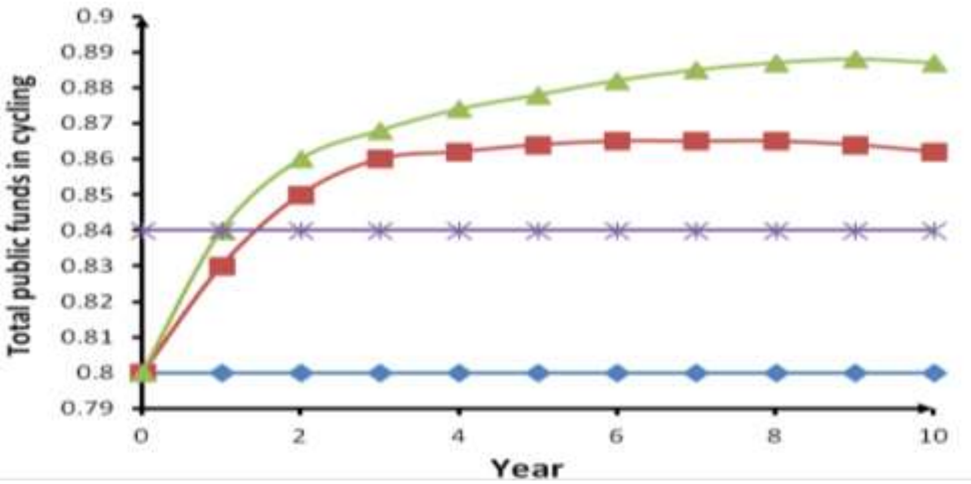


Figure 19 SD Model Result: Public Funding Levels for a City with High Initial Cycling Levels (Annual expenditure in million$ per 10,000 population)

Model Findings and validity

The model suggests that for a given level of public investment, to increase cycling modal share, it is better to improve cycling infrastructure than to finance bike-share. Indeed, bike sharing offers many other benefits that are not explicitly accounted for in the analysis (e.g. other alternatives for people to move around the city, environmentally friendly, also contributing to reduced traffic congestion, etc.) The results support the view, however, that public fund investments may be used more productively if invested in cycling infrastructures, as opposed to bike sharing. Analyzing the impact of other benefits is beyond the scope of the analysis, and provides an opportunity for future work.

As evidenced by the static or even decreasing cycling modal share in the base cases, an increase in cycling infrastructure investment is a key requirement to push up cycling adoption for commuting. Bike-sharing systems alone are not effective in increasing cycling modal share in commuting in the long run. In a city-state like Singapore with scarce land availability, deploying more infrastructures for cycling might be a challenging process. The feasibility of such recommendation should be investigated further alongside the policy makers, and provides another opportunity for future work.

Structural validity is supported by ensuring the variables used in the model exist in real life cases, and are supported by actual observable relationships (e.g. Fig. 12-15). Further, we check the model outputs for different scenarios, especially for the extreme values of the variables. Our model holds good in all these cases (Fig. 16-19) when compared with real values of cycling modal share in different cities with bike-sharing systems (DeMaio 2009, Midgley 2011, OBIS 2011, Shaheen, Guzman and Zhang 2010, Velib 2012).
Though, very limited time series data is available for cycling modal share and ridership on the bike-sharing systems due to their recent origin (Capital Bikeshare 2012, DeMaio 2009, Midgley 2011, Shaheen, Guzman and Zhang 2010, Velib 2012); there is hardly any impact on the commuter cycling levels in the cities (Paris, Barcelona, Montreal, Boston, Washington DC, London) due to bike-sharing systems. Besides, all these bike-sharing systems are loss-making, thus requiring public funds continually in a direct or indirect manner (e.g. foregoing of advertising revenue). These observations are in line with our model findings. On the other hand, cities like Amsterdam, Copenhagen and Tokyo have a high cycling modal share (more than 20%) despite absence of a big publicly funded bike-sharing system. However, these cities invest heavily in cycling infrastructure and have policies in place to make cycling safe (Keijer and Rietveld 2000, Pucher and Buehler 2008, Pucher and Dijkstra 2000).

The Proposed Systems Approach to Policy-making

Real-life policy making is always under constraints. Financial implications, political acceptability and difficulties in implementation due to control or technology related issues play a key role. Furthermore, evaluation of policies on stand-alone basis using benefit-cost analysis approach would give unrealistic results due to presence of complex feedbacks and inter-linkages amongst different policies. Taking a systems perspective, we suggest an alternative portfolio based approach to policy making. In this approach, for the given financial and political constraints, different portfolios of policies may be evaluated to pick the most effective set of policies. It could be a combination of policies with different time frames (short to long-term), different mechanisms (pull or push policies) and different revenue and political implications to suit the specific constraints.

In the proposed framework, public policies, directly or indirectly related to commuter cycling, are classified into '**Effective', 'Helpful'** and **'Adverse'** categories based on their contribution in promoting commuter cycling. In **Figure 20**, these policies are mapped on to their revenue implications to assess their financial impact, as investment requirement of policies is a major decision criterion in most of the city governments, especially in developing countries. Furthermore in **Figure 21**, these policies are categorized based on their '**implementation difficulty'** level which includes political, technological and control issues leading to difficulty in adoption of the policies. We clarify that our purpose in proposing this framework is to demonstrate the importance and use of systems thinking in policy making. The detailed classification of policies as shown in **Figure 20** and 21 is based on a qualitative, somewhat subjective interpretation of academic literature, and its applicability as well as scope of various policies is open to debate.

The proposed generic classification is suggested as a methodological approach for the practitioners involved in urban transport policy and planning. They can use these classification bins to shortlist, combine and sequence policies to develop an effective policy portfolio to promote commuter cycling for a city.

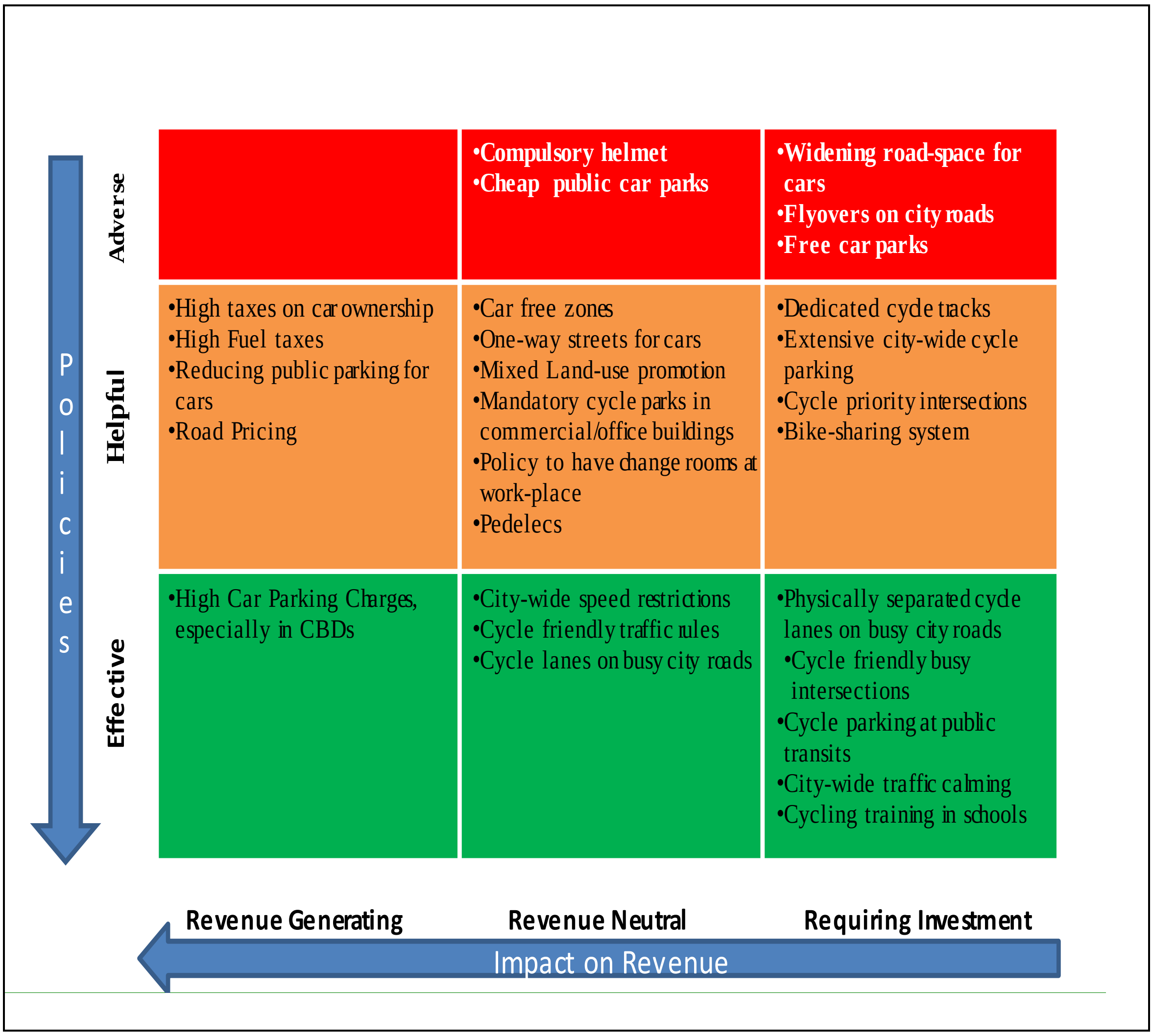


Figure 20 Classification of Cycling-related Policies based on Effectiveness and Impact on Revenue

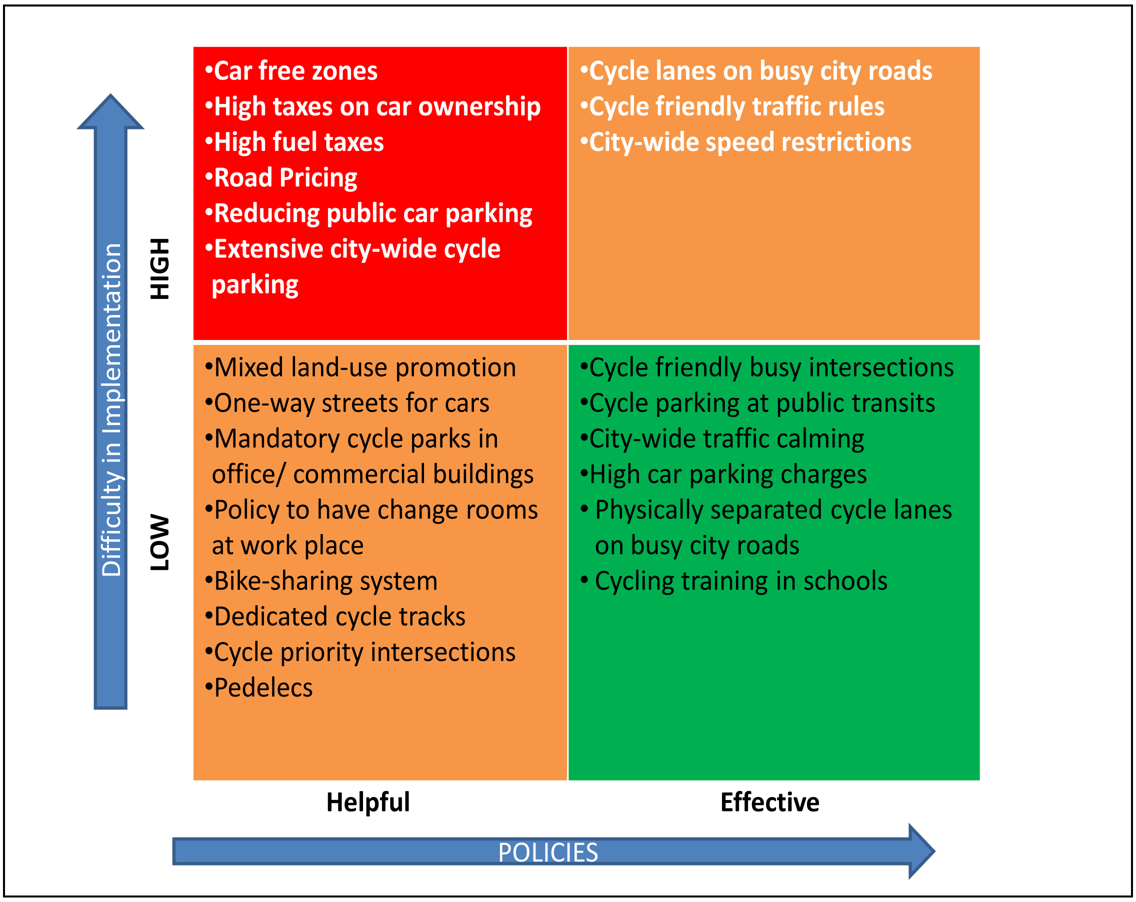


Figure 21 Classification of Cycling-related Policies based on Effectiveness and Implementation Difficulty

Chapter Conclusion

In this chapter we take a systems perspective to understand the effectiveness of bike-sharing systems and to develop a framework to implement policies to promote commuter cycling in urban mobility. Through use of systems thinking, as supported by causal loops and SD modelling, we understand the dynamics of various policy levers.

We find that the effective policies to promote commuter cycling, last-mile cycling in particular, include: provision of safe, preferably separate, cycling infrastructure along the busy commuter corridors and approach to transit stations; extensive bike parking at important locations such as transit stations;

and wide-spread traffic calming on city roads. Active discouragement of car usage through speed, priority and parking controls can also play an important supplemental role. Moreover, land-use policies promoting compact, mixed-use developments and transit-oriented development can help shorten the trip lengths and make cycling more attractive. Implementing these policies in a well-coordinated manner over the long-term can help bring about higher cycling levels, introduce a cycling culture and make cycling a choice mode in addressing the urban mobility problem.

While bike-sharing systems may enlarge the reach of public transport and increase the number of cyclists and cycling trips, they are neither sufficient nor necessary in promoting cycling. Conversely, high cycle modal share can only be achieved and sustained with a safe, extensive and continually improving cycling infrastructure. Instead of spending public funds on bike-share, city governments should invest directly in cycling infrastructure to create an environment where cycling is an attractive commuting option. When that happens, individuals can buy and use their own bicycles, thus rendering bike-share systems non-essential. However, this study assumes that the public funds are limited and an investment in bike-sharing projects reduces the fund availability for cycling infrastructure. If bike-sharing projects are funded through private sources, the dynamics would be different and conclusions from our model may not hold good.

Finally, much of cycling infrastructure is a public good which does not attract private investment. Governments may promote private investment in bike-sharing projects by offering appropriate incentives, while ensuring that cycling infrastructure development will come first.

Using this knowledge we find out a portfolio of effective policy interventions and a rationale to sequence them under the given political, financial and other implementation constraints. We classify these policies based on the common city constraints of budget and implementation difficulty.

In the next chapter, we build on our findings about commuter cycling policies and further use farecard data to estimate commuter cycling demand and to suggest policies to promote last-mile as well as end-to-end cycling in Singapore.

Chapter- 3
Commuter Cycling Policy in Singapore: A Fare-card Data Analytics Based Approach

Introduction

Though cycling can play an important role in urban mobility, there is not enough research on how to assess commuter cycling potential and where to plan for cycling infrastructure in cities (Heinen 2011, Mcclintock 2002, Pucher, Dill and Handy 2010, P. Rietveld 2001). Besides, there is a paucity of reliable cycling demand data and the planning process is often driven more by passion and less by reason. Furthermore, policies intended to promote cycling in general may end up benefitting recreational cycling without encouraging more commuters to cycle (Heinen 2011, Buehler and Pucher 2012).

In Singapore, the modal share of commuter cycling is around 1% and is not considered a mainstream option. Besides, there is a lack of comprehensive studies to make policies for cycling (Barter 2008).

This paper tries to address the above mentioned research gaps. First, it surveys the academic literature to understand different types of commuter cycling, its key determinants and the policies that should matter most in the case of Singapore. Second, it assesses the potential demand for commuter cycling in Singapore through the analysis and spatial visualization of farecard data. Third, we propose an optimization-based decision support model to make efficient policy choices for maximizing commuter cyclists. This paper leverages the availability of a rich farecard data-set provided by the Land Transport Authority (LTA) of Singapore. Hence, it also indirectly sheds light on the key information that needs to be captured through farecards in different cities to enable a similar analysis.

Urban Mobility in Singapore: Role of Commuter Cycling

Current Mobility Situation, Policies and Perspective

Singapore has pioneered innovative urban transport policies in electronic road pricing and vehicle quota system, and has an extensive network of rail and bus based public transportation. There are more than 300 bus services and the current Mass Rapid Transit (MRT) network includes 102 stations with 148km of rail-route (LTA 2012). **Figure 22** shows the MRT network as of 2012.

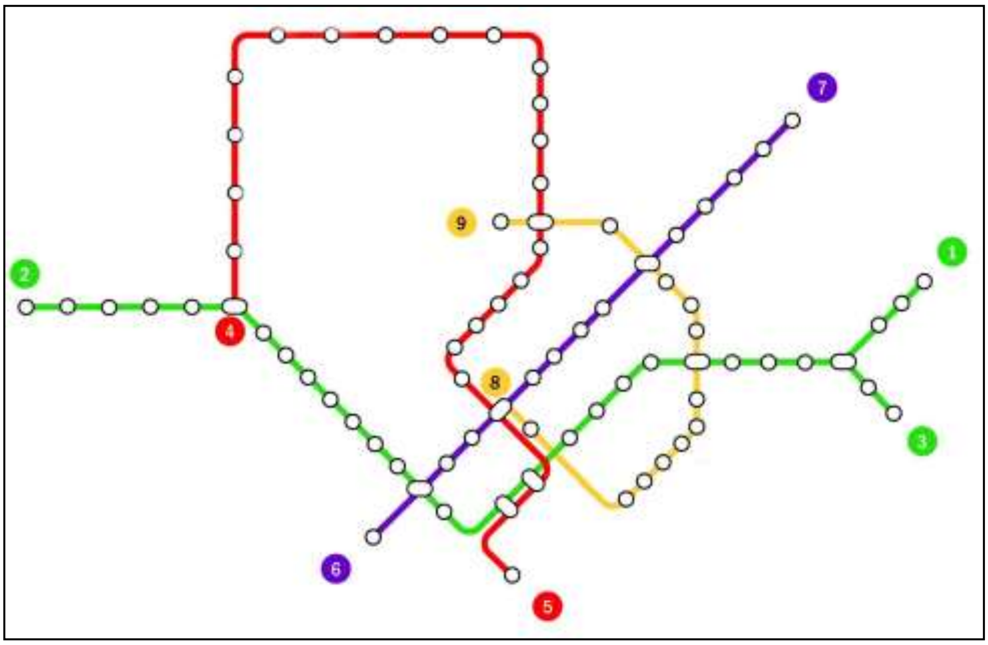


Figure 22 MRT Network in Singapore (June 2012)

Despite a good public transport network, Singapore faces a trend of declining public transport share along with an increase in car usage. The modal share of public transport declined from 63% in 1997 to 56% in 2008 (Cheong and Toh 2010). Amongst public transport modes, bus and taxi modal shares have gone down *(***Figure 23***)* while the MRT share has gone up. It is partly explained by the speed advantage of MRT over buses, especially during peak-hours (**Figure 24**) when average bus speed nosedives. Further, **Figure 25** shows that not only the modal share of buses has gone down but also the average trip length has declined from 5.4 km in 2005 to 4.5 km in 2011 (LTA 2006, LTA 2011, LTA 2012). It suggests that buses are losing popularity for longer commutes and are being used more for shorter distance trips.

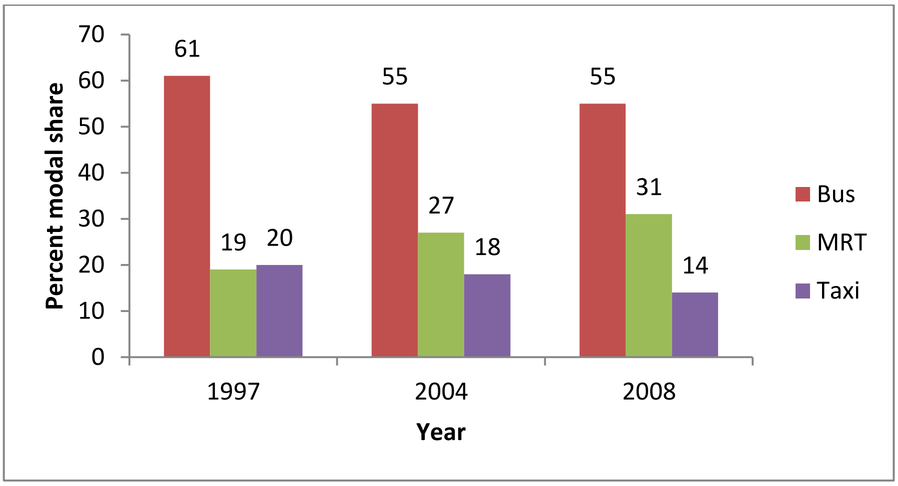


Figure 23 Modal Share within Public Transport including Taxis(HIT Surveys)

Though increase in MRT's modal share is partly due to its network expansion, its efficiency for longer commutes has also helped it to become a popular mode of public transport. The Household Interview Travel (HIT) Survey (2008) suggests that even people in high-income groups, who are more likely to own cars, frequently use MRT because of its comfort and speed (Cheong and Toh 2010). There is also an increase in use of cars for feeder (first/last mile) trips by more than 50%: from 0.5 million trips in 1997 to 0.78 million trips in 2008 (Cheong and Toh 2010). This trend not only demonstrates increasing acceptance of MRT as an efficient mode for commuting, but also highlights the inadequacy of existing feeder services.

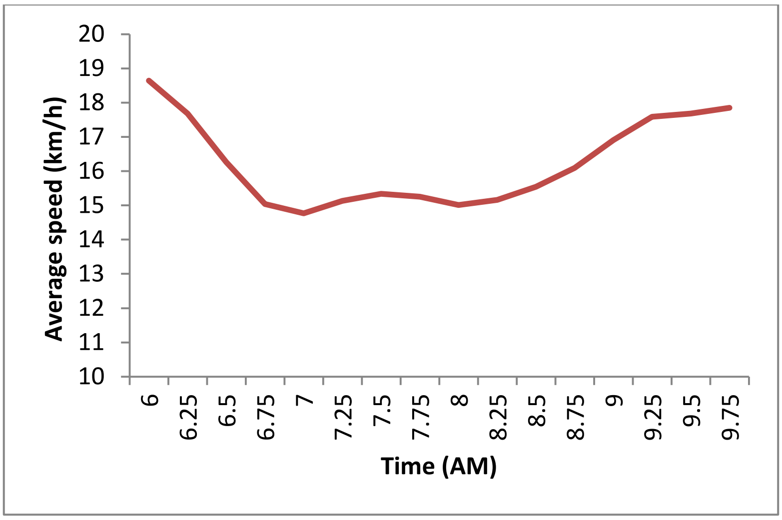


Figure 24 Decline in Bus Speed during Morning Peak (EZ-link data analysis, 11- 15 April 2011)

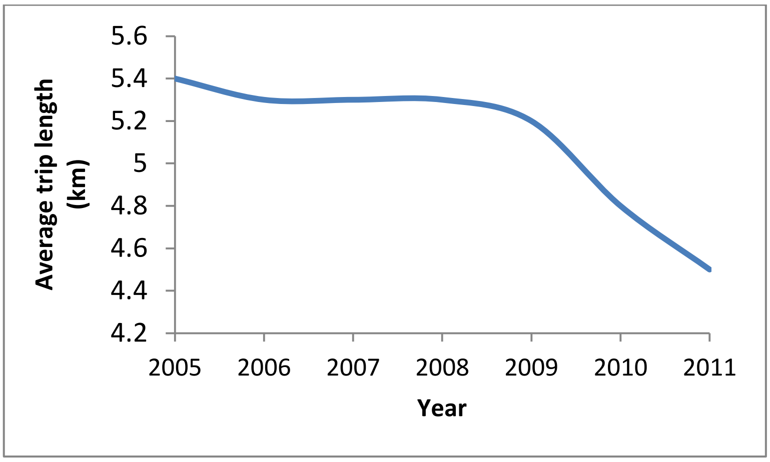


Figure 25 Declining Trend in Average Bus-trip-length (LTA data)

Accessibility of MRT stations emerges as a key criterion for the ridership of mass transits. HIT survey (2008) results show that more than 70% of commuters living within walking distance of transit stations prefer to take the MRT, but this percentage sharply drops to less than 40% at a distance of 2 km. An explanation of this behaviour could be the fact that the first-mile access often consumes disproportionately large amount of time and effort over the whole journey and makes public transits less competitive vis-a-vis car.

Facing these facts, the government of Singapore is investing heavily to expand MRT network to make it mainstay of public transport network. LTA plans to increase the MRT network from the existing 148 km in 2012 to 278 km by 2020. This will make Singapore mass transit network comparable to New York and London in terms of density. In the city centre area, there would be at least one MRT station within five minute walk from any point (Ministry of Transport 2011). That means there should be no need for a feeder service at the work-end of MRT trips to the city area. Besides MRT expansion, Singapore government plans to spend $1.1 billion over the next 10 years (2012-22) to improve feeder bus services. The target is to decongest feeder services and improve their frequency to 6 minutes on most routes (Shanmugaratnam 2012).

With these key interventions, the land transport master plan (LTMP) 2008 aims at increasing the mode share of public transport from 59 per cent during morning peak hours in 2008 to 70 per cent by 2020. The objective is to make public transport more competitive vis-a-vis car in all respects, especially with respect to total travel times (Ministry of Transport 2012).

While expansion of MRT network would bring more people with in walking distance of transit stations and would reduce their travel times, still a large part of population would need to use some other mode for the first-mile. Though investment in improving the feeder bus services would be helpful for the above pupose, it would be costly and loss-making to improve the quality of service substantially without raising the effective fares. Besides, there are inherent issues of reliability of buses with respect to arrival and travel time which are difficult to address (Lee et al 2012). Promotion of commuter cycling could provide an efficient, competitive, low-cost alternative to feeder buses and private cars for the first-mile. It could also alleviate many short distance end-to-end car and public transport commutes (Barter 2008, Heinen, Wee and Maat 2010).

Evaluating Cycling as a Commuting Option in Singapore

Cycling offers many benefits to problems of urban mobility. Apart from being a clean, cheap and equitable mode of transport for short-distance journeys, cycling can potentially reduce traffic congestion, parking space requirements and roadway costs (Mcclintock 2002, Heinen et al 2010). It is one of the most sustainable and efficient transportation modes for trips of distance up to around 5 km (Midgley 2011, Buehler 2010). Consequently, it has a place in a policy maker's tool-kit of urban mobility solutions, especially for short distance trips. Safety, comfort, convenience and acceptability/status of cycle as a mainstream transport mode are the key drivers of commuter cycling. Except for natural barriers, public policies may address and improve many of these factors (Buehler 2010, Pucher and Buehler 2008, Barter 2008). However, for longer trips cycling becomes uncomfortable and inefficient. Besides, changing the trip length distribution requires long-term urban planning policies. Hence, practically, short trip length is a major pre-requisite to encourage commuters to cycle (Ellison and Greaves 2011, Heinen, Wee and Maat 2010, Brunsing 1997).

Adverse weather and topography can make cycling challenging. In Singapore, during morning commuting hours, the prevalent temperature rarely exceeds 27C, though humidity often exceeds 80%. Many research studies suggest that these are reasonably good conditions for cycling. Moreover, there are studies showing that regular cycle commuters are not very sensitive to temperature changes unless these are rather extreme (Heinen et al 2010, Nankervis 1999, Moreno Miranda and Nosal 2011). Rainfall affects cycling levels temporarily but is not a major constraint at aggregate level, as evidence from many European cities with heavy rainfall suggests (Buehler 2010, Heinen et al 2010). While data also suggests that cycling decreases when gradient exceeds 4% (Heinen et al 2010), it is not a deterrent in Singapore as it has a largely flat terrain.

Effective integration of cycling with transit may increase the catchment area and ridership of transits. It can also improve the overall efficiency of public transport by reducing the need for feeder buses (Krizek and Stonebraker 2010, Martens 2004). Many commuters can also cut down their total travel times by cycling to MRT stations rather than taking feeder buses (Ellison and Greaves 2011, Keijer and Rietveld 2000). Hence, in Singapore, the potential for commuter cycling is likely to grow with the expansion in MRT network requiring more short-distance feeder trips, though some existing feeder trips may also be obviated due to the expansion of MRT network.

In Singapore, a low public image of commuter cyclists could be a challenge to begin with (Barter 2008, Tay 2012). However, with sustained improvement in infrastructure and with subsequent increase in usage of cycling by well-off commuters, this is likely to change overtime.

The above discussion shows that there are no major natural constraints to commuter cycling in Singapore, and public policies can encourage commuters to switch to cycle mainly for the short-distance trips, preferably up to 3 km, for the first-mile (home-transit) connections (Heinen, Wee and Maat 2010, Keijer and Rietveld 2000, Koh, et al. 2011). These short-distance trips could either be the first-mile trips as a part of a public transit journey or could be the end-to-end trips. Further, the literature shows that commuters may cycle relatively longer distances, up to 5km, for the end-to-end trips compared to the first-mile trips (Pucher and Buehler 2008).

Current Status of Cycling in Singapore

Though current cycling levels in Singapore are only around 1% of work-trips, government agencies recognise the increasing role of cycling as an alternative option for short-distance trips to MRT stations and transport hubs (Ministry of Transport 2012, Barter 2008). As a part of a national cycling plan, the LTA rolled out an intra-town cycling programme in 2009. It involved the construction of more than 45km of dedicated off-road cycling tracks in five Housing Development Board (HDB) towns- Tampines, Yishun, Sembawang, Pasir Ris and Taman Jurong- by 2014. Two more towns - Bedok and Changi Simei – have been added to the list besides a plan to develop more than 16km of cycling paths in the Marina Bay area by 2014 (LTA 2012). These cycling paths would link the residential areas to transport nodes and local amenities . Demand and community support for cycling are the main criteria for the selection of cycling towns (LTA 2010). LTA has also planned the addition of more than 2500 bicycle parking racks at MRT stations and bus interchanges by 2013 (Ministry of Transport 2012, LTA 2012).

In Singapore, there also exist more than 200 km of park connectors, which is the network of off-road pan-island cycling paths joining various parks (National Parks 2012). There are plans to increase it to 300km by 2015 (Koh, et al. 2011). Though, it was built primarily for recreational cycling, it can be leveraged to create opportunities for commuter cycling.

Methodology and Data Description

Literature survey suggests that trip distance is the key criterion which determines whether a trip is bike-able or not. Hence, we consider the assessment of short-distance commuting trips a good indicator of the potential trips that can be shifted to bicycle.

We consider two types of trips which can be shifted to cycling: the first mile and the end-to-end trips. With Singapore's MRT system, there exist a large number of feeder (first-mile) short-distance trips by bus and car to MRT stations. These trips can be completed more efficiently by cycling. Based on a literature review, we find out that most commuters prefer to cycle for the first-mile up to 3 km. Hence, we take 3 km as the cut-off trip distance to assess first-mile cycling potential. For the end-to-end trips, based on the research literature, we take relatively higher value of 5 km as the maximum distance. Through farecard analysis, we find spatial distribution of first-mile and end-to-end trips centered around MRT stations.

We treat first-mile and end-to-end trips differently, as the policies required, as well as the impact on the transport system, is different for both in many respects. While first-mile trips require cycling infrastructure and facilities centered around MRT stations, end-to-end trips need network of cycling infrastructure along the whole route, as well as cycling facilities at destinations (offices, factories, business district, schools etc.). While cycling for the first-mile helps in increasing the efficiency and ridership of public transport, end-to-end cycling can reduce short-distance car, bus, as well as MRT trips. The potential of cycling to school is assessed separately as policies need to stress more upon safety, training and communication with parents.

Finally, we develop an optimization based decision support model to make an efficient choice of policies/projects to maximise potential cyclists for a given investment level. Inputs to the model include cycling demand numbers, cost estimates of cycling infrastructure, percentage switch to cycling from different modes for first-mile and end-to-end trips and investment levels.

Data Description, Cleaning and Processing

To assess commuter cycling potential in Singapore, we need information about trips made during peak-hours through different modes. We are privileged to have a unique farecard dataset originating from Singapore's public transportation network. This fare card, called EZ-link, was introduced in 2003 (EZ-link 2012). These farecards are widely used for seamless distance-based payment across buses and MRT, and cover more than 96% of all public transport trips (Prakasam 2009). This farecard data provides detailed trip information including trip origin and destination, trip start and end timings, trip lengths, and details of transfers across public transportation modes. Singapore is one of the few cities that capture such comprehensive data about public transport usage, especially the destination data, which opens up a myriad of possibilities for using analytics. Data for car trips (including private car, taxis, etc.) is not readily available; however, we can assume that the Singapore public transport flows represent the global travelling patterns. Consequently, we use LTA's farecard data to approximate the number of trips which can be converted to cycling from different modes.

The farecard data that we shall use corresponds to five consecutive weekdays (from 11th April 2011, Monday to 15th April 2011, Friday). Since there were no school or office holidays during this period, these data are a good representation of typical working day peak flows. We consider a time frame from 6.30AM to 9AM for our analysis as this interval not only captures the morning peak hour traffic but weather conditions are also more suitable for cycling.

The database stores all public transportation trips made during the day, including bus, MRT and LRT. By definition, one journey of a passenger may compose of several trips. Each trip is identified by the unique card number of the passenger, passenger type (child, adult, senior), origin, destination, service number (for bus), tap-in time, duration, trip distance as well as the sequence number of the trip in the journey. From the unique card number, we can filter all the trips made by a specific passenger, and using the tap-in time and the sequence number, we can build his whole itinerary. The sequence number allows us identify the first and last mile of the journey, with the distance directly available through the database.

The passengers may create false entries by several ways: forgetting to tap out at exit (resulting in missing values in duration and trip distance), tap-in and out at the same stop (resulting in distance of 0). We remove all these bad entries from the database, along with other entries made by the same card number to avoid noise. All manipulation of the data and statistical analysis are done using R (a programming language and software environment for statistical analysis).

Data Analysis and Key Observations

First and Last Mile Trips

More than 120,000 commuters use feeder buses daily to take a first-mile trip (mainly home to MRT station) for a subsequent MRT trip. **Figure 26** shows the distance distribution of first mile trips up to 5km distance. A large percentage of these first mile trips is less than 3km long which is a good distance to encourage switch to cycling. Most of these trips are made by adults with students accounting for less than 5 percent of all first-mile trips. On the other hand, less than 7,500 commuters take a last-mile trip (MRT station to work-place) by feeder bus after completing their MRT trip. It suggests that last-mile (work-end) feeder trips are small in number compared to the first-mile (home-end) feeder trips. Hence we shall not pay much attention to last-mile (work-end) trips in our analysis.

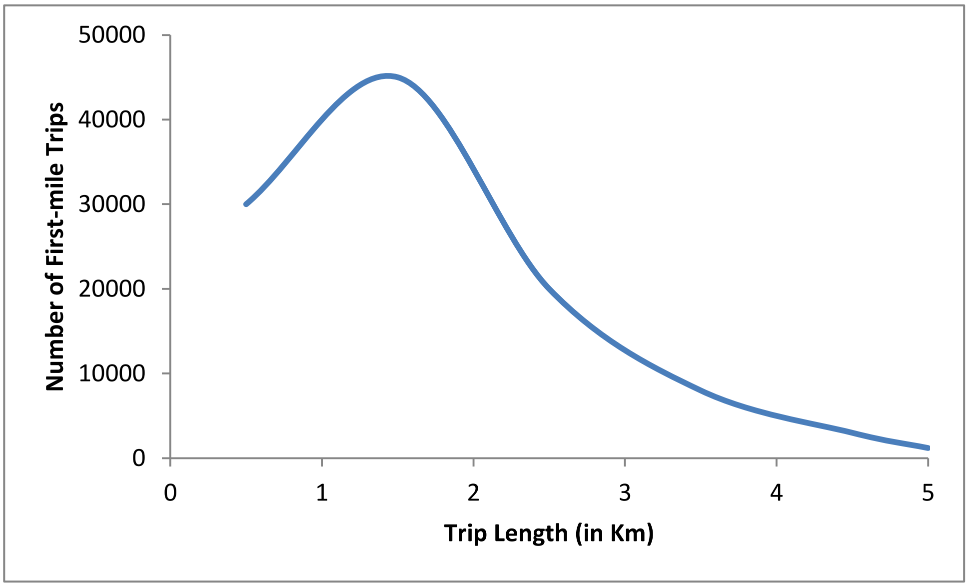


Figure 26 Distance Distribution of First-mile Trips (6.30AM to 9AM)

Figure 27 shows the spatial distribution of these short distance (less than 3km) first mile trips to MRT stations with the area of each bubble proportional to the number of these first mile trips. We use red to represent the seven planned cycling towns under the LTA cycling plan, and green to represent the potential cycling towns based on the number of first mile trips. Despite having more than 100 MRT stations, most short distance first mile trips are concentrated in suburban, residential towns such as Tampines, Ang Mo Kio and Bedok. Consequentially, 19 MRT stations, as shown in **Figure 28**, can cover up to 71% of all these first mile trips. This spatial distribution supports the development of a cycling infrastructure in the neighbourhood of these stations.

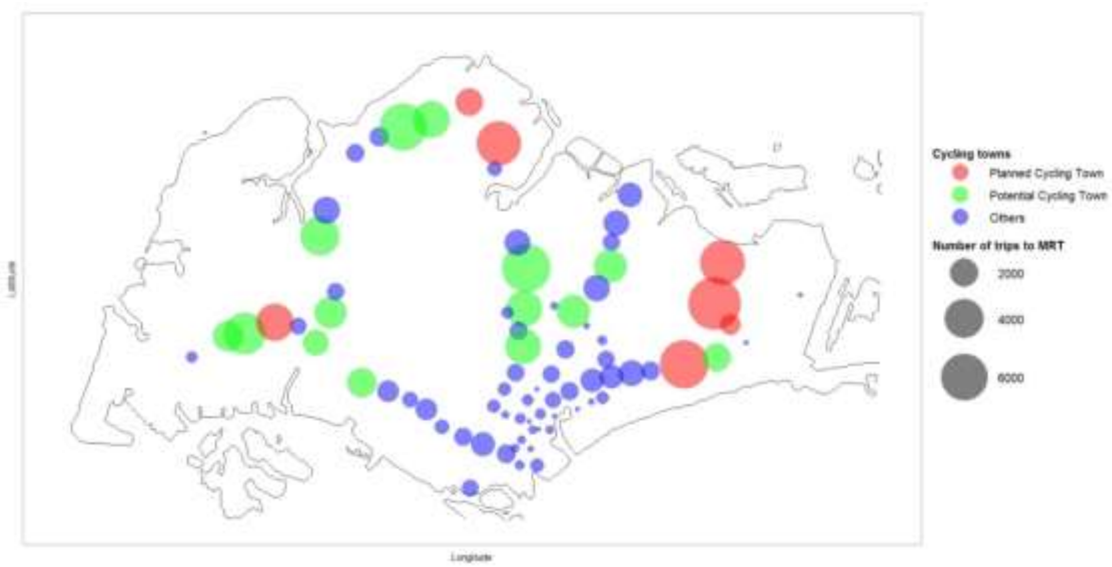


Figure 27 Spatial Distribution of First-mile Trips to MRT Stations (6.30AM to 9AM)

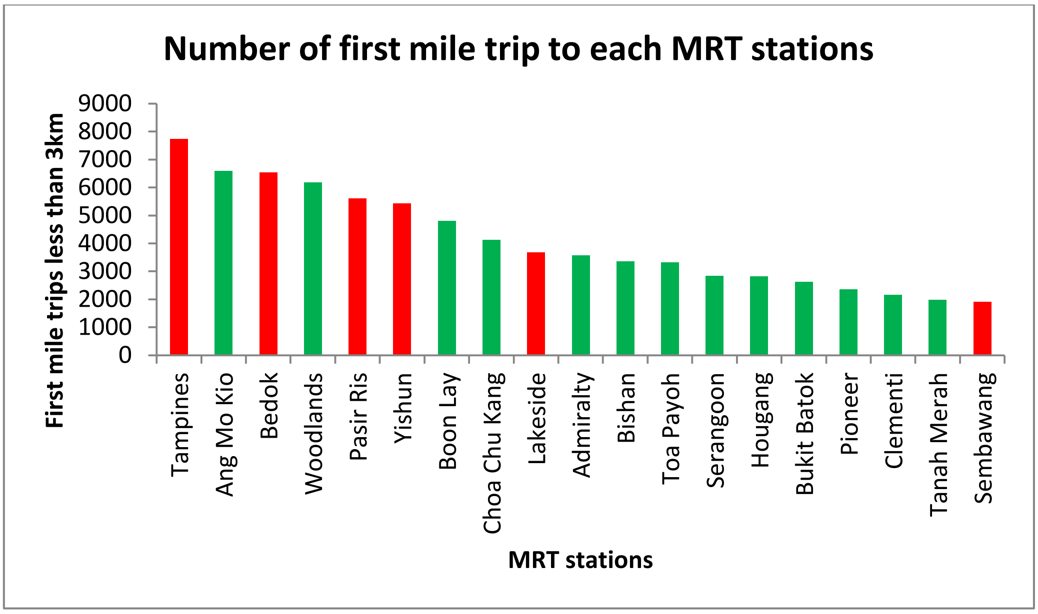


Figure 28 First-mile Trips to MRT Stations (LTA's Planned Cycling Towns in Red)

There is also a large number of first-mile trips by car (drop-offs). Though the distance and spatial distribution of these car trips is not available, we can assume it to be similar to feeder bus trips. HIT survey (2008) estimates number of service trips (drop-off and pick-up to public transport) at 775,000 daily. Assuming that 30% of these service trips take place during morning (6.30AM – 9AM) hours and 50% of drop-offs occur at MRT stations, we estimate car based first-mile trips as 116,000 which is almost equal to bus based first-mile trips.

End-to-end Trips

A high percentage of morning commuting journeys are less than 5km in distance: around 25% of all morning public transport commuters undertake an end-to-end short-distance (less than 5 km) journey, of which 58% are adult (not including senior citizens), and 28% are student/child. Figure 29 shows that around 70% of the students' trips are of less than 3km length. However, the origin and destination (OD) pairs as approximated by MRT and bus stations) for most of the journeys are dispersed geographically over the whole island. In **Figure 30**, we plot the links representing the OD pairs with at least 100 trips with darker links for heavier flows, and most of these pairs connect MRT stations. It is, however, difficult to depict spatially other short distance, low volume bus flows on account of a large number of bus stops, each of which is a unique origin as well as destination. From **Figure 30**, we can see that there are heavy short distance flows to the Central Business District stations like City Hall and Raffles Place. Furthermore, there are also significant flows in the west (Jurong, Boon Lay) and the north (Woodlands) regions. These flows suggest a significant potential for end-to-end cycling along these links.

Further we assume that end-to-end trips by car also have similar distance and spatial distribution. As MRT modal-share is around 20% of all trips (public plus private), the end-to-end short-distance flows, as shown in our analysis, represent only 20% of all short-distance end-to-end flows.

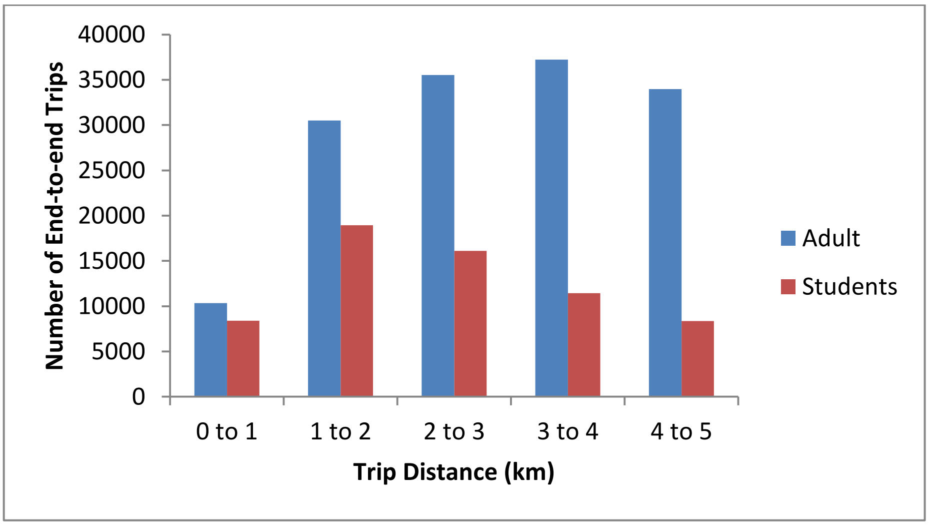


Figure 29 Short-distance End-to-end Trips (6.30AM TO 9AM)

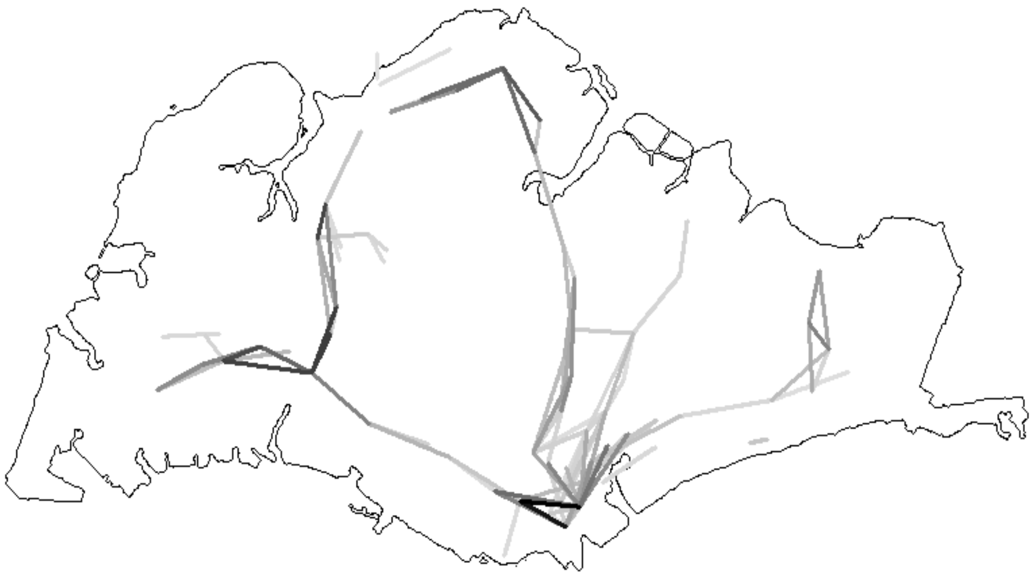


Figure 30 Spatial Distribution of Short-distance Trips (darker the line, larger the flows)

As the number of students taking short end-to-end trips is significant, we also track the OD pairs for students separately. However, we consider only OD pairs of less than 3km distance here, which is more suitable for cycling by kids. We consolidate the OD pairs by the destinations to identify hot spots with large number of inward journeys. We find that the towns like Choa Chu Kang, Lakeside and Tampines, have a large number of end-to-end short-distance school trips, most of which have secondary schools, junior college or ITE as their destinations. These trips can be efficiently shifted to cycling.

Policy Recommendations and Decision Support Model

Policy Recommendations

From the analysis in the last section, there are many insights we can draw upon to propose commuter cycling policies. The first recommendation is about the promotion of cycling towns to realize the potential of first mile cycling. LTA has already selected seven cycling towns for development. From **Figure 28**, we can confirm that the potential for first mile bicycle trips is substantial in six of these towns (except Changi-Simei), especially in Tampines, Bedok, Pasir Ris and Yishun which have a large number of first-mile trips. Besides, based on first-mile demand analysis, we suggest that additional towns like Woodlands, Ang Mo Kio and Boon Lay could be developed into cycling towns in future. Apart from the potential demand, LTA should consider the feasibility and cost aspects of different cycling towns to implement intra-town cycling.

As a second recommendation, we propose the planning of cycling regions to promote end-to-end commuter cycling. Since end-to-end cycling requires not only the integrity of cycling routes but also good cycling infrastructure and facilities at both ends, adjoining cycling towns with significant inter-town flows can be linked through cycling tracks or cycling lanes in order to promote inter-town cycling. From **Figure 31**, we can identify three possible cycling regions: East, North and West cycling regions, wherein size of each circle indicates number of last-mile trips. Anchored with LTA's planned cycling towns, these regions could be expanded gradually by developing the potential cycling towns and inter-town link networks. We depict the West cycling region as an illustration in **Figure 32** with nodes representing the MRT stations. The number inside each node is the first mile demand to the MRT station, while the links depict the end-to-end flows coupled with the corresponding demand.

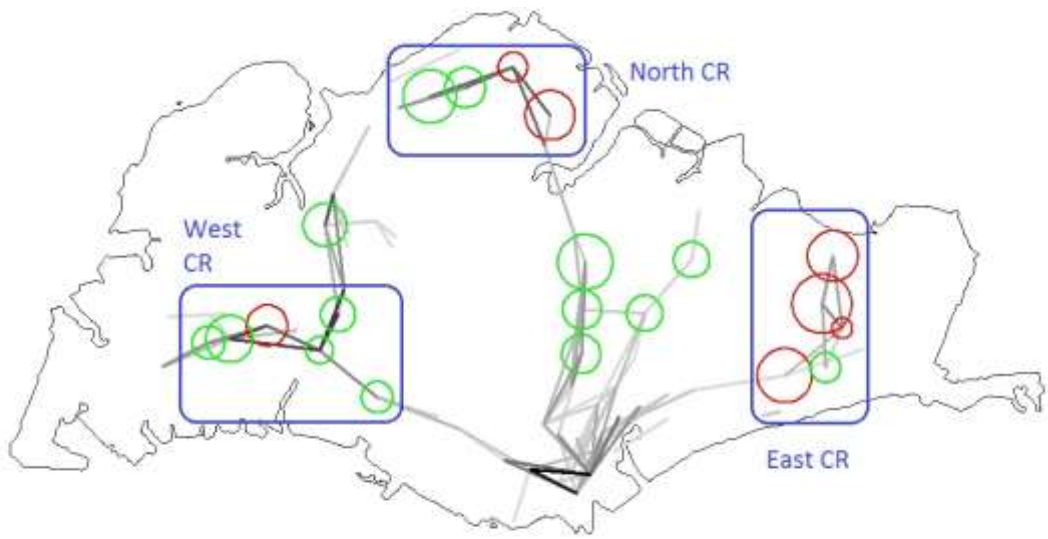


Figure 31 Proposed Cycling Regions (CR) on Singapore Map

Development of cycling regions can be facilitated by the existing island-wide park connector network. More specifically, the east and north cycling regions can take advantage of the existing eastern coastal loop and the northern explorer loop respectively. By providing connections between cycling towns, cycling regions may serve a larger population and a richer variety of trips than the development of cycling towns alone. However, since public funds are limited, all possible cycling towns and links cannot be picked up simultaneously. Hence, in the next section, we propose a decision support model to make the most efficient selection of cycling towns and links.

The central business district (CBD), the area with heavy flows in the south-central region of **Figure 31**, is also the destination for a large number of short-distance commuter flows. However, it may be difficult to develop cycling infrastructure along the busy roads to CBD due to space constraint. Hence, we have not identified it as a potential cycling region despite heavy flows.

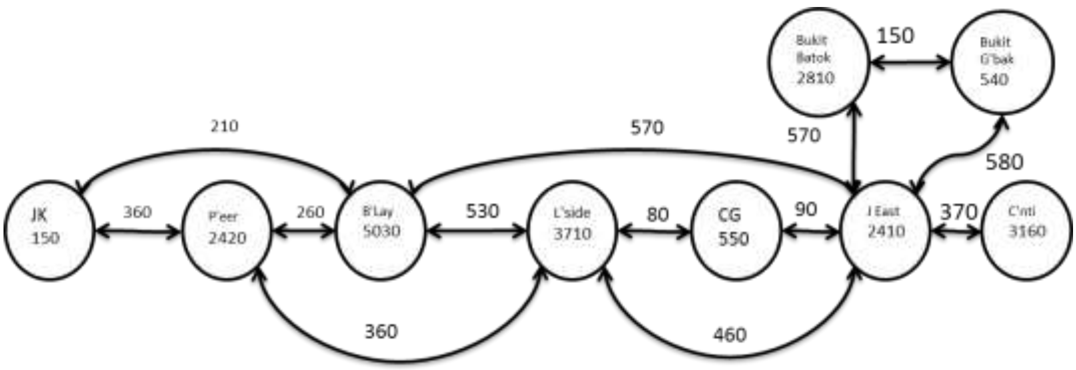


Figure 32 West Cycling Region's Cycling Flows

Finally, we recommend the concept of school cycling enclaves in areas where a high proportion of end-to-end cyclists are students. From the OD analysis of students in the previous section, we find that Choa Chu Kang can emerge as a future school cycling enclave. With a relatively high concentration of schools, especially secondary schools and junior college/ITE, Choa Chu Kang generates high flow of students in its neighborhood. These flows can be shifted to cycling easily if higher standards of safety are ensured. Therefore, school-centric cycling enclaves would require the development of safety focused cycling infrastructure around schools and deeper community involvement to encourage parents to support cycling by students.

Apart from the policies related with infrastructure, research literature points out the importance of other soft policies such as public education, law enforcement and work-place policies in encouraging modal switch to cycling. All these policies should be implemented in an efficient, coordinated manner with active community involvement. However this paper does not cover these aspects in detail.

Decision Support Model

In this section, we propose an optimization model to support the policy makers in making better choice of cycling towns and cycling regions as suggested in the previous section. While choice of cycling towns apparently looks straightforward with policy makers picking MRT stations in decreasing order of first mile demand, the integration within cycling regions introduces a higher level of complexity. On one hand, this complexity arises from a large number of end-to-end demands which are sparsely distributed over the island. On the other hand, each cycling link can serve multiple end-to-end demands at the same time. For example, considering three cycling towns in a straight line A-B-C : link A-B serves not only demand from A to B and vice versa, but also demand between A and C. This results in a higher complexity of the decision process, thus the need for our decision support model.

In this model, we assume that the policy maker will build cycling towns centered at MRT stations. This assumption is reasonable for the case of Singapore and is further reinforced by LTA's choice of current cycling towns in the neighborhood of MRT stations. Development of cycling infrastructure around MRT stations better serves the purpose of providing first and last mile transportation.

Furthermore, we make the assumption that each cycling link has to connect two cycling towns to ensure accessibility as well as smoothness of cycling trips for the end-to-end demand. Indeed, if the cycling town is not developed, the cyclists may have difficulties at the first or the last mile, which reduces the attractiveness of the cycling option. In our model, a cycling link can refer to a cycling track or a cycling lane depending on engineering considerations.

Let $G = (N, E)$ be a graph representing the MRT stations in Singapore, with N be the set of MRT stations and E be the set of edges connecting two adjacent stations on the MRT line. At each MRT station $i \in N$, there is a cycling first mile demand d_i. The set C contains all short distance end to end demand, and each demand $c \in C$ has an origin $o(c) \in N$, a destination $d(c) \in N$ and with cycling demand of a_c. For a time horizon T, the benefit of serving one cyclist is b. The cost of building a cycling town at MRT station i is h_i, and the cost per km to build a cycling track connecting station i and j is k_{ij}.

We denote $CT \subseteq N$ as the set of MRT stations with existing cycling town, and $CL \subseteq E$ be the set of existing cycling links. The cost for existing cycling towns and existing cycling links are taken as zero.

The variables are denoted as follows:

$$x_i = \begin{cases} 1, \text{ if a cycling town is to be developed at MRT station } i \\ 0, \text{ otherwise} \end{cases}$$

$$y_{ij} = \begin{cases} 1, \text{ if a path is to be built to connect two stations } i \text{ and } j \\ 0, \text{ otherwise} \end{cases}$$

$$z^c = \begin{cases} 1, \text{ if demand } c \text{ is satisfied} \\ 0, \text{ otherwise} \end{cases}$$

$$f_{ij}^c = \begin{cases} 1, \text{ if demand } c \text{ flows from station } i \text{ to station j} \\ 0, \text{ otherwise} \end{cases}$$

The optimization model with the objective of maximizing potential net benefits is:

$$\max\ b\left(\sum_{i\in N} d_i x_i + \sum_{c\in C} a_c z^c\right) - \sum_{i\in N} h_i x_i \tag{P1}$$

Subject to:

$$\sum_{(i,j)\in E} f_{ij}^c - \sum_{(j,i)\in E} f_{ji}^c = \begin{cases} z^c, & o(\text{c}) = i \\ -z^c, & d(\text{c}) = i \\ 0, & otherwise \end{cases} \qquad \forall c \in C, \forall i \in N \tag{1.1}$$

$$y_{ij} \le x_i \qquad \forall (i,j) \in E \tag{1.2}$$

$$y_{ij} \le x_j \qquad \forall (i,j) \in E \tag{1.3}$$

$$f_{ij}^c \le y_{ij} \qquad \forall c \tag{1.4}$$

$$x_i = 1 \qquad \forall i \in CT \tag{1.5}$$

$$y_{ij} = 1 \qquad \forall (i,j) \in CL \tag{1.6}$$

$$y_{ij} \in \{0,1\} \qquad \forall (i,j) \in E \tag{1.7}$$

$$f_{ij}^c \in \{0,1\} \qquad \forall c \tag{1.8}$$

$$x_i \in \{0,1\} \qquad \forall i \in N \tag{1.9}$$

$$z^c \in \{0,1\} \qquad \forall c \in C \tag{1.10}$$

The objective of (P1) is to maximize the net benefit of the policy. Constraint (1.1) is a flow conservation constraint, which ensures that if the demand c is satisfied, there will be a possible flow from the origin to the destination of the demand. Constraints (1.2) and (1.3) ensure that the cycling paths connect two cycling towns. Constraint (1.4) forces the flow to be on cycling paths. Constraints (1.5) and (1.6) capture the existing cycling towns and cycling paths.

However, in real life, there are uncertainties as well as inaccuracies in the benefit calculations, especially in context of commuter cycling as it involves monetization of externalities related with congestion, air pollution and health, besides estimation of direct savings and valuation of travel time savings. Any projection of these benefits would vary depending on the choice of the methodology and assumptions about local circumstances. Besides, policy decisions related with transport infrastructure have long-term behavioural as well as environmental implications which cannot be captured in a limited time horizon. Hence, we propose an alternative simple approach to policy-making based on the demand maximization where the policy maker may want to maximize the number of cyclists within a total budget of M_B.

$$\max \sum_{i \in N} d_i x_i + \sum_{c \in C} a_c z^c \qquad (P2)$$

Subject to:

Constraints (1.1) to (1.10)

$$\sum_{i \in N} h_i x_i + \sum_{(i,j) \in E} k_{ij} y_{ij} \leq M_B \qquad (2.1)$$

In this model, the objective is to maximize the cycling demand which can be satisfied. The additional constraint (2.1) gives the restriction on the budget. In cases where policy-makers may want to constrain the number of cycling towns M_{CT}, and the number of cycling links M_{CL} to be developed, we may replace constraint (2.1) by the following two constraints:

$$\sum_{i \in N, i \notin CT} x_i \leq M_{CT}$$

$$\sum_{(i,j) \in E, (i,j) \notin CL} y_{ij} \leq M_{CL}$$

Both models (P1) and (P2) are binary linear programming problems, which can be solved using commercial solvers such as CPLEX or Gurobi.

Experimental Results

Model (P2) requires data concerning cycling demand, the cost of developing cycling towns, the cost of building cycling paths and the budget available. Although not all of this data is available for Singapore, it can be approximated from the literature or from historical data.

Our first approximation is for the percentage of commuters switching to cycling from different modes. This percentage is used to calculate the first mile and the end to end cycling demand. **Table 1** summarizes the modal share of commuter cycling in different cities. In good cycling towns, the overall commuter cycling modal share is generally more than 20%. Unfortunately, there is no data available exclusively for the end-to-end cycling modal share. In this model, we use a conservative approximation of 10% of first mile and end-to-end short distance commuters switching to cycling.

Regarding the cost, it can be approximated from LTA's report (LTA 2012) about expenditure on cycling towns. LTA plans to spend $43 million for the first 5 cycling towns, consisting of building 30km of new cycling tracks. As a result, the cost of developing a cycling town is estimated at $10 million, and the cost of building a cycling link is $0.5 million per km. The unit distance cost of the cycling link is below the average cost taken from the LTA's report because the cycling infrastructure available in cycling town reduces the requirements of new constructions for cycling links.

Table 1 Modal Share of Commuter Cycling across Cities

City name	Overall Commuter cycling modal share	First-mile cycling modal share (% of all transit trips)
Amsterdam	34% (Buehler 2010)	N.A.
Copenhagen	36% (Pucher and Buehler 2008)	25% (Martens 2004)
Denmark (avg)	35% (Pucher and Buehler 2008)	N.A.
Netherlands (avg)	32% (Pucher and Buehler 2008)	30% (Martens 2004)
Germany (avg)	28% (Pucher and Buehler 2008)	N.A.
Tokyo	N.A.	20% (Andrade and Kagaya 2011)
Osaka	N.A.	25% (Andrade and Kagaya 2011)
Nagoya	N.A.	35% (Andrade and Kagaya 2011)

N.A. means not available

For sensitivity analysis, we compare the solutions with different levels of available annual budget, which are described in **Table 2**. The nominal budget available is taken as $100 million based on per capita annual expenditure of €13 on cycling related infrastructure in Amsterdam as Dutch cities are considered good examples of commuter cycling (Pucher et al 2010). The low and high scenarios are taken as ±30% of the nominal value.

Table 2 Budget Values for Three Scenarios

	Low	Nominal	High
Budget	$70 Millions	$100 Millions	$130 Millions

As an initial condition, the seven cycling towns from the current LTA plan are considered as existing cycling towns in the model. The solutions are shown in **Figure 33** to **Figure 35** with circles showing the cycling towns (red circles depicting planned cycling towns) and black lines showing the cycling links.

From this result, the northern cycling region is fully justified for all three scenarios of the available budget; this strongly supports the construction and development of cycling towns and cycling links in the area. On the other hand, the western and eastern cycling regions can only be partially implemented despite the strong inter-flows between cycling towns as shown in **Figure 31**. The full implementation of these two cycling towns would require a higher budget to make it feasible. Based on the potential demand, some cycling towns and links close to CBD are also picked up as shown in **Figure 33** to **Figure 35**. However, its implementation would be relatively difficult as it involves development of cycling infrastructure in densely built up area.

With the increase in the budget, there is a tendency to invest more in cycling towns. This may be due to the high first-mile demand to the MRT stations. There is also a consistency in the cycling towns chosen for development throughout the three scenarios, though there is a minor inconsistency with one cycling link. This fact suggests that the planner can use this model for incremental implementation as well.

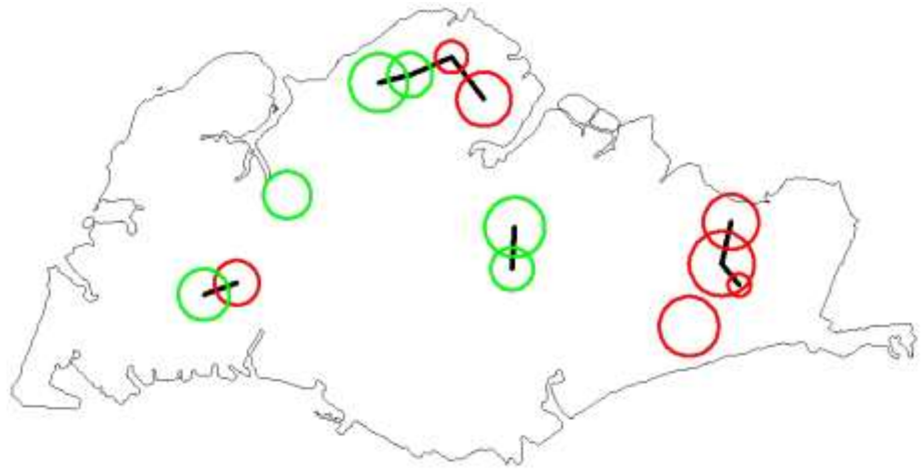


Figure 33Solution of the Optimization Model with budget of $70 million

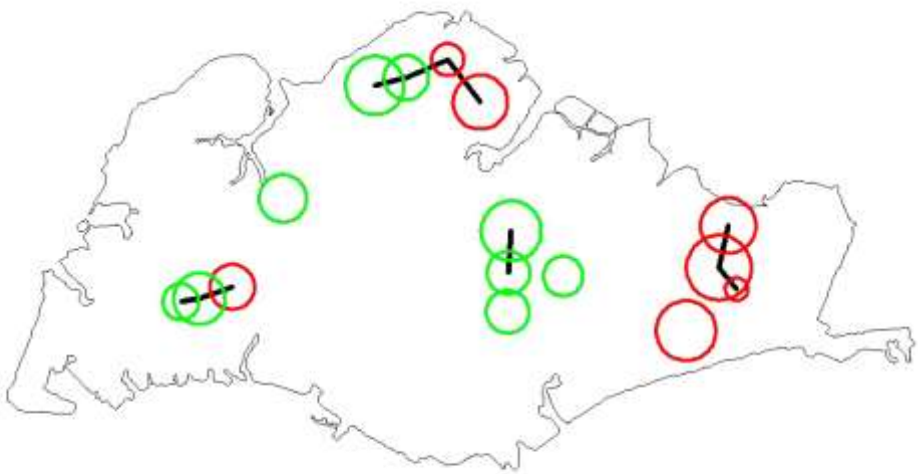


Figure 34 Solution of the Optimization Model with budget of $100 million

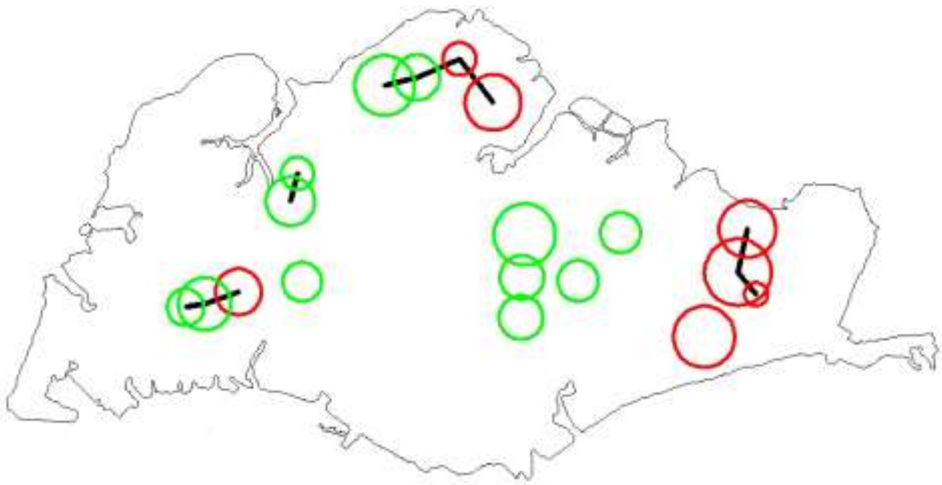


Figure 35 Solution of the Optimization Model with budget $130 million

This decision support model is a practical tool for city wide planning of cycling infrastructure for a given budget constraint. Reliability of the model can be improved through better estimates of cycling infrastructure cost and modal switch percentages for different towns and links. More specifically, the infrastructure cost shall be different depending on the urban form of each town and choice of infrastructure design. The cycling demand can be estimated better by taking into account the private vehicle flows, or even the walking patterns. Furthermore, the percentage of commuters who switch to cycling from different modes would vary depending on local circumstances. These are open questions for future research.

Chapter Conclusion

Commuter cycling can play a significant role in alleviating morning peak-time congestion in many cities. Through fare card data analysis, this paper confirms good potential of commuter cycling for the first-mile as well as end-to-end trips in Singapore. However, it should be realized that these demand estimates are based only on the trip distance criterion while there may be many other factors that determine variation in commuter cycling demand across different areas with in a city as well as across cities.

Commuter cycling can encourage use of MRT by providing an efficient option for first-mile (home-end) trips. It can provide an efficient alternative to feeder buses besides substituting many first-mile trips by car. Many short-distance end-to-end trips can also be travelled by bicycles.

In this chapter, we give three main policy recommendations to promote commuter cycling in Singapore. These recommendations include suggestion of more cycling towns, developing cycling regions and advocating the concept of school cycling enclaves. As these policies are based on better understanding and visualization of the demand through farecard data analytics, the policy-making process becomes more objective and transparent.

We also propose an optimization model as a decision support tool to make efficient choice of cycling towns and links for a given budget constraint. As suggested in the paper, it can be a useful tool for efficient policy making.

The farecard in Singapore captures information about the origin, destination as well as transfers involved in a public transport journey. Availability of this data is a pre-requisite to apply the proposed methodology to assess commuter cycling demand. Hence other cities should also collect this information through their farecards to enable a similar analysis.

However, different cities face different challenges in last-mile accessibility and it requires a deeper understanding of the last-mile related problems to come up with efficient, comprehensive solutions. Hence, in the next chapter, we understand the role of last-mile issues in metro ridership through a large survey of commuters in Delhi around the metro rail stations.

Chapter-4
Last-mile Access and Transit Ridership: Case Study of Delhi metro

Introduction

The literature talks about a variety of factors affecting ridership on metro[5] systems. One of the key factors is last mile[6] connectivity (Cervero 1998, Cheong and Toh 2010, Mohan 2008, Givoni and Rietveld 2007). Most of the literature on the last-mile access focuses on solving the efficiency and level of service related issues for feeder services like fleet sizing, vehicle routing and demand responsiveness (Cordeau and Laporte 2007, Blainey, Hickford and Preston 2012). There is also some research focusing on promotion of non-motorized modes like walking and cycling for the last-mile (Martens 2004, Krizek and Stonebraker 2010). However, the economics of last-mile solutions and their suitability in different contexts, especially in the the developing world, are not well researched. Through a case study of Delhi, this paper focuses mainly on the economic aspects of the last-mile access and its impact on the metro ridership. This paper is unique in the sense that it presents data from an extensive commuter survey in Delhi and examines issues specific to the city. However, the observations should be applicable to other similar cities and may be useful to transport planners in general.

We find that lack of an affordable and efficient last-mile access is a key reason for a relatively low ridership on certain Delhi metro lines. Further, based on

[5] Metro refers to a metro rail system (heavy rail with largely underground or elevated rail tracks)

[6] In this paper, we use 'last-mile' for both first-mile and last-mile connections to/from metro rail stations.

the insights from our analysis, we evaluate and recommend last-mile policies in Delhi.

Delhi Metro: Background and Ridership Issues

Public transport in Delhi: Evolution and issues

Delhi is the largest urban agglomeration in India. Its population is projected to grow from 23 million in 2012 to 33 million by 2025 (United Nations 2012). It consists of India's capital New Delhi along with many satellite cities like Gurgaon, Noida and Faridabad. Delhi has witnessed a phenomenal growth in private motorized vehicles by more than 12 times from 0.56 million in 1981 to 6.9 million in March 2011 (Delhi Government 2012). It has caused an increase in traffic congestion and environmental pollution. Inadequacies in public transport have exacerbated the situation.

Till 2002, conventional buses were the mainstay of the public transport system in Delhi. Though a commuter rail[7] system is also in service, its ridership is very low due to limited network coverage, poor frequency and accessibility issues (Reddy and Balachandra 2012). Planning for a new rail-based underground/elevated mass transit had started in Delhi in the 1950s. However, the first concrete step towards construction of the metro was initiated in 1995 with creation of the Delhi Metro Rail Corporation (DMRC). Physical work on the project started on October 1, 1998 and the first metro line was opened in December 2002. As in January 2014, the Delhi Metro system comprises six[8] lines, numbered 1 to 6, with a total length of around 190 km and 142 stations

[7] A surface rail system with tracks shared with inter-city passenger as well as freight trains.
[8] Excluding airport line, Lines 2 and 3 pass through the central business district and transport hubs of the city. Line 4 is a branch of line 3. Line 2 is notionally subdivided into two-lines called 2N and 2S , where N and S stand for north and south portions of the line respectively.

(phase 1 and 2) as shown in Figure 36. There are plans to expand Delhi Metro’s network to 370 km by 2020 (DMRC 2011). Delhi metro is widely considered an engineering success story for its quality construction without any time or cost overruns. However ridership numbers continue to be less than expected.

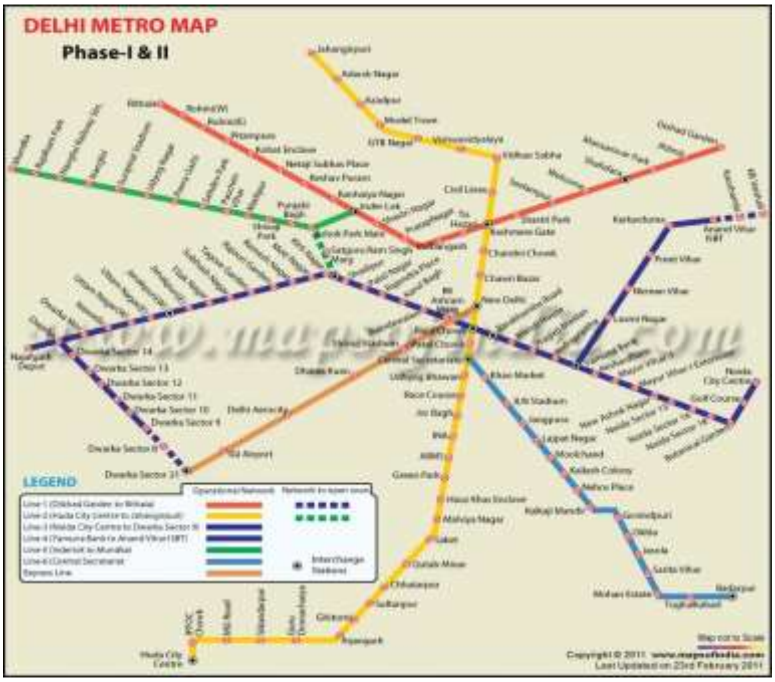


Figure 36 Delhi Metro-rail Map

Delhi Metro: Ridership Forecasts and Trends

Different ridership forecasts were made for Delhi metro in different project reports. The initial detailed project report for phase 1 of Delhi metro had forecast a daily ridership of 3.18 million in 2005 over a network of around 60km (RITES 1998). After observing actual daily ridership of 0.6 million in 2003, subsequent project report in 2005 scaled down the forecast to 2.8 million passengers per day in 2011 (RITES 2005). However, despite a larger network of around 190 km, the daily ridership was more than 25% less than the revised projection at around 2.1 million in December 2012 (DMRC 2012).

Delhi metro had a low modal share of about 7% of all non-walk trips in Delhi in 2012 as shown in **Figure 37** (RITES 2012). According to various project reports, its modal share was estimated to exceed 20% by taking traffic away from buses, cars and motor-cycles (RITES 2011, Advani and Tiwari 2005). However, buses, private motorbikes and cars are the most popular modes respectively.

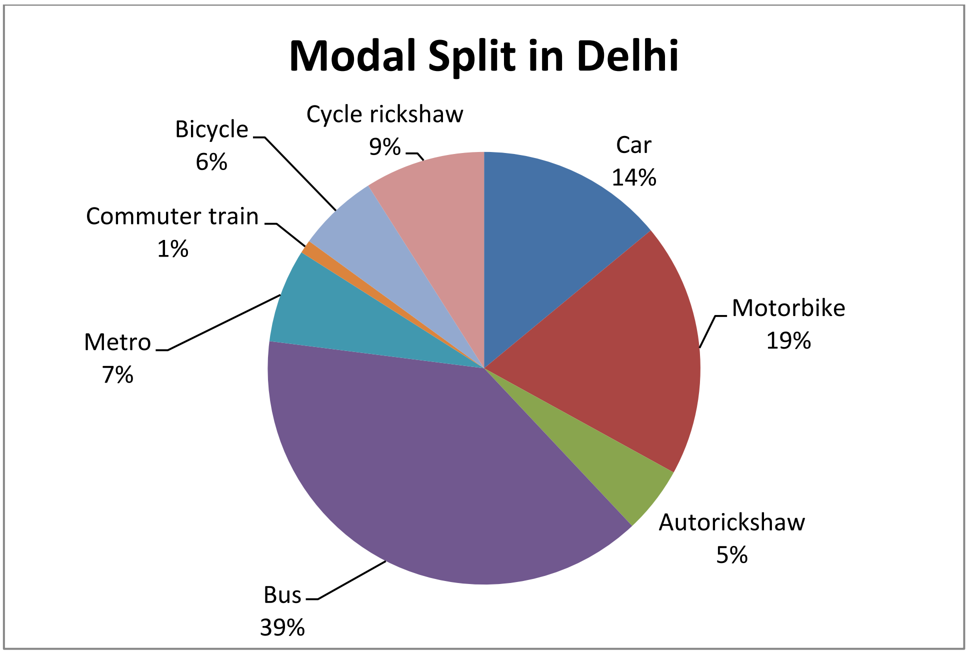


Figure 37 Modal Split in Delhi (2012)

Peak-hour capacity is a key design consideration as well as constraint for the metro systems. Actual peak-hour traffic on Delhi metro is much less than the projected traffic as well as designed capacity. **Figure 38** shows the line-wise actual peak hour ridership on metro as compared to the projected ridership and design capacity. It is obvious from **Figure 38** that the ridership is low on lines 5 and 6.

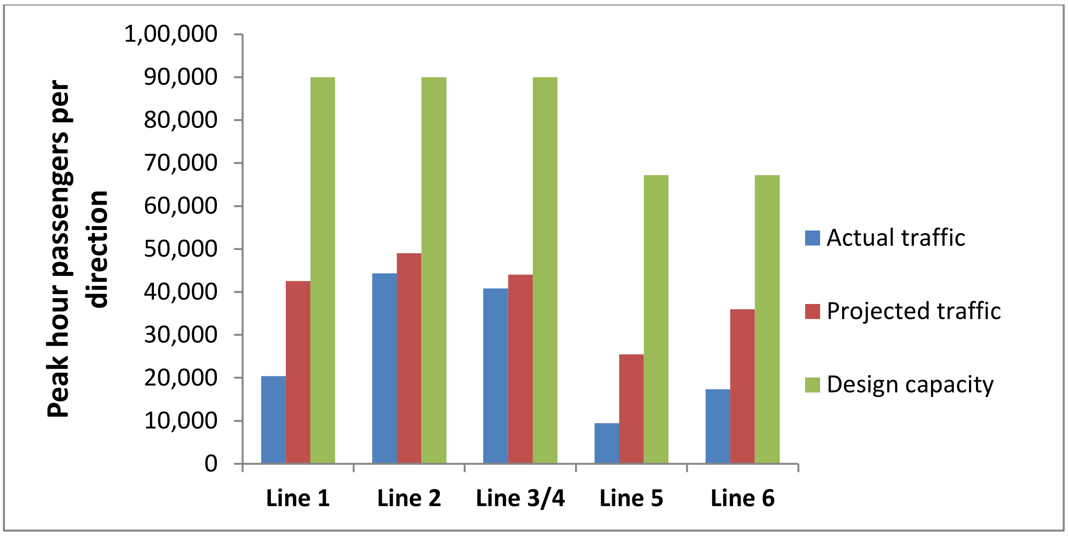


Figure 38 Peak-hour Ridership

(Source: Actual traffic taken for Sept 2012, projected peak traffic in 2012 as per RITES 2005 report; design capacity taken for minimum headway, maximum train length and 8 standees per square metre)

Based on a large sample of cities of different sizes, the literature suggests existence of a positive relationship between population density and metro rail ridership (Bertaud and Richardson 2004). However, an international comparison of 16 largest (ridership) metro systems (as shown in **Figure 39**) suggests that high population density doesn't guarantee high metro rail ridership. In case of Delhi, despite a high population density, per-capita metro ridership is quite low in comparison to most big cities in the developed as well as the developing world (**Figure 39**). The above facts suggest presence of some other important factors that affect metro ridership adversely.

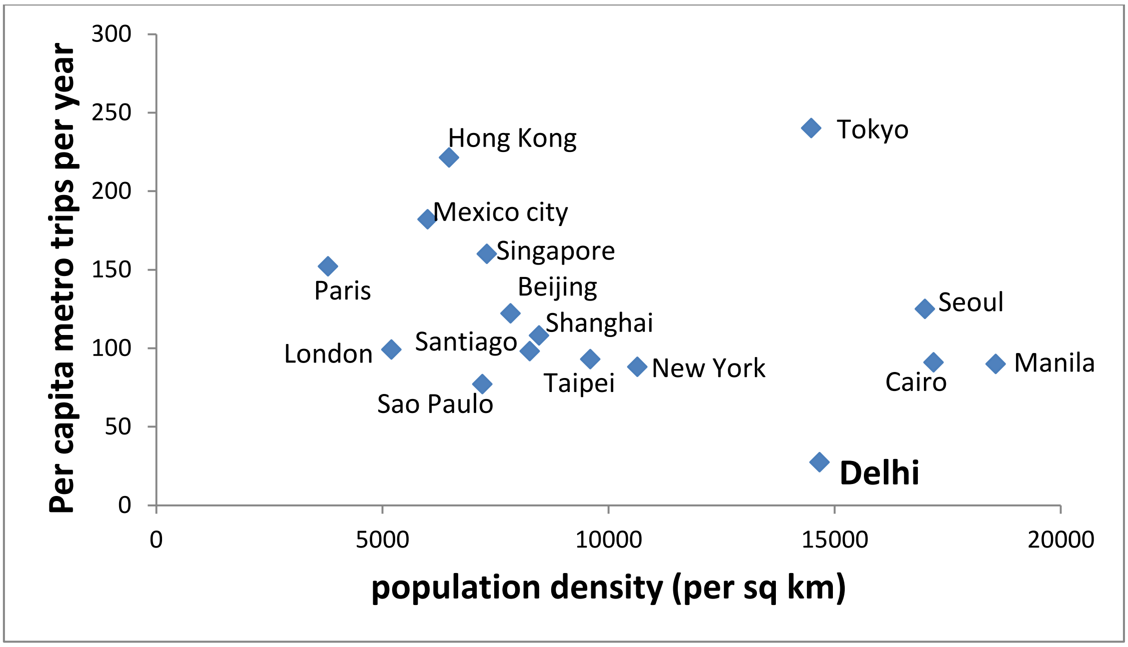


Figure 39 Metro Ridership and Population Density: International Comparison

Further study of ridership patterns, based on the Delhi metro data for September 2012, reveals that the average trip length on Delhi metro is 15.1 km, which is more than double the estimated trip length of 7.12km, as mentioned in the project reports (RITES 1998). **Figure 40** shows the distance distribution of metro trips: about two-third of all trips are longer than 10 km, while more than one-fourth of all trips are even longer than 20km. This is despite the fact that more than 75% of daily trips on all non-walk transport modes in Delhi are of less than 10km length as shown in **Figure 41** (Mohan 2008, RITES 2012).

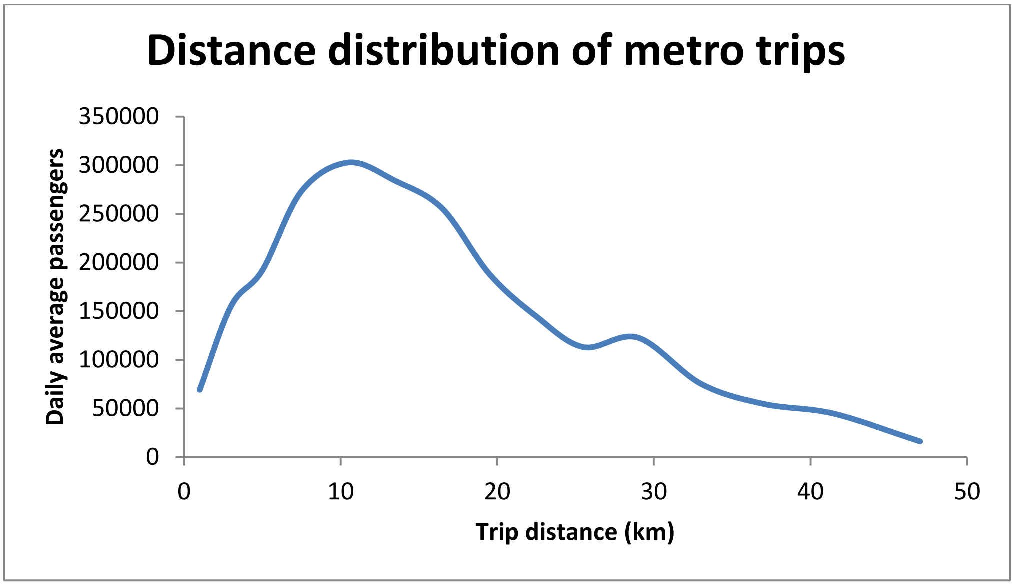


Figure 40 Distance Distribution of Delhi Metro Trips (Sept 2012)

(Source: Based on daily ridership data as provided by DMRC for the month of Sept 2012)

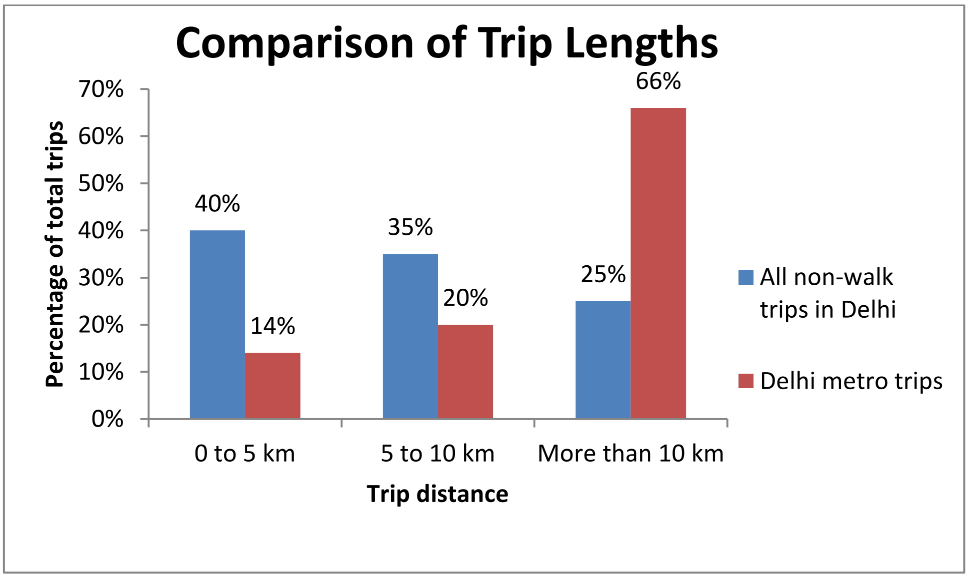


Figure 41 Comparison of Metro Trip-length vis-a-vis all Non-walk Trips in Delhi

(Source: (RITES 2012); Sept 2012 data from DMRC)

An international comparison of average trip length on Delhi metro with some large metro systems around the world shows that trip distances on Delhi metro are much longer than the typical trip lengths on a metro system (**Figure 42**).

Metro users in Delhi apparently prefer to use it mainly for longer trips. This, in turn, suggests that Delhi metro suffers some competitive disadvantages vis-à-vis other modes (bus, motorcycles, cars) for short distance trips.

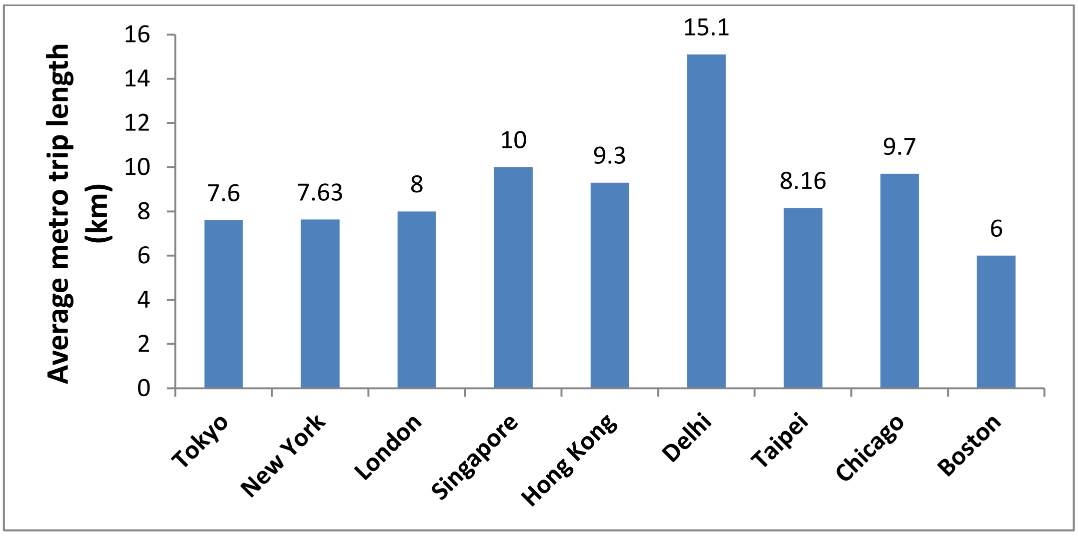


Figure 42 Average Metro Trip Length: International Comparison

A conceivable explanation for the aversion of commuters to making short-distance trips by metro could be a lack of good last-mile services. A metro trip is preceded and succeeded by a last-mile trip to complete an origin to destination journey. The cost, comfort and efficiency of the last-mile mode can be an important factor affecting transit ridership as the last-mile trips often consume a disproportionate amount of time, money and effort of a mass transit based commute. Commuters can reach metro stations by walking, cycling, riding a feeder bus, car or motorbike. Walking is an efficient last-mile option for distances up to around 800 metres while cycling can be an efficient and cost-effective mode for last-mile trips up to 3km in many cities (Ellison and Greaves 2011, Katia and Kagaya 2011, Martens 2004). If there are no good options for a non-walk last-mile trip, many commuters, who have to make a non-walk last-mile trip, may find metro rail uncompetitive vis-à-vis bus/motorcycle/car for a short journey as no last-mile trip may be required for bus and car/motor-cycle. In other words, metro rail may lose its time and/or cost advantage vis-à-vis other modes if last-mile trips are costly or inefficient.

Metro Fares, Last-mile Cost and Metro Ridership

Comparative fares, as a function of trip distance, for different public transport modes in Delhi are shown in **Figure 43**. Metro is the costliest of all the modes. Moreover, as compared to a bus trip, a metro trip may require an additional non-walk last-mile trip on either end of the journey which makes it even costlier. Though commuter rail is the cheapest mode in Delhi, its ridership is very low (less than 1%) mainly due to limited network and poor accessibility of stations (Reddy and Balachandra 2012).

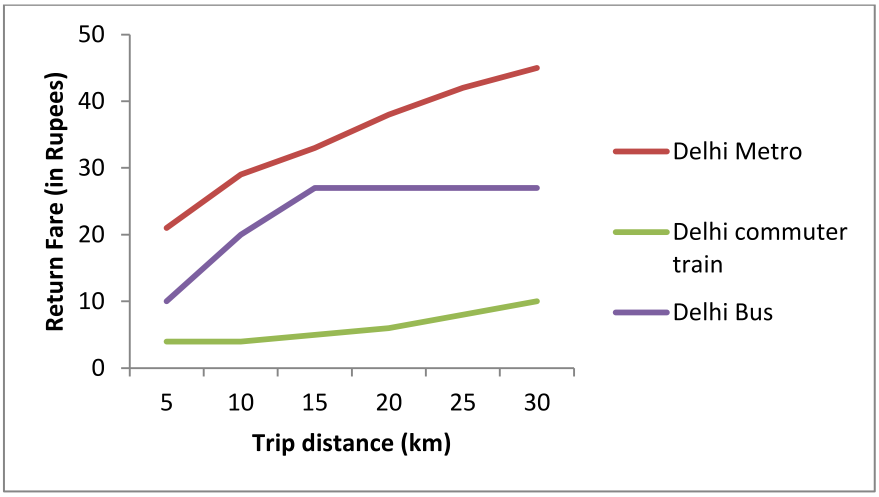


Figure 43 Delhi Metro Fares as Compared to Bus and Commuter Rail

Next, we make an international comparison of Delhi metro fares to get the right perspective. **Figure 44** shows the relationship between metro ridership (annual per capita metro trips) and affordability of metro fares (return metro fare as a percentage of daily per-capita income) for 16 major metro systems (same as in **Figure 39**), while **Figure 45** shows the relationship of metro ridership and affordability of last-mile inclusive effective metro fare or these cities. We find that the last-mile inclusive fares have a stronger correlation with the ridership numbers than the metro fares alone. Hence, as the last-mile cost to travellers decreases, metro systems become more price competitive vis-à-vis other modes and vice-versa. For example, low ridership in Delhi, as compared to London and Sao Paulo, is better explained by a higher last-mile inclusive (effective) cost of a metro trip to a large fraction of commuters in Delhi (Figure 45). Return metro-train fare in Delhi costs an average commuter 7% of his daily income, but if he has to take a para-transit for the last-mile, his effective cost of a metro commute more than doubles to 14%, making it unaffordable to a large segment of commuters.

Figure 44 Metro Ridership and Affordability of Metro Fares

(Source: (DMRC 2012, Wikipedia n.d., Tokyo Metro n.d., MTR n.d., Cairo Metro n.d., Metro de Santiago 2012, Metro Taipei n.d., LTA 2012, MTA n.d., Wikipedia n.d.), nominal GDP per capita taken (2011-12). For Cairo, Tokyo, Paris, Manila, Singapore, Hong Kong and Mexico city: average values for the country taken; for other cities, city specific GDP values taken)

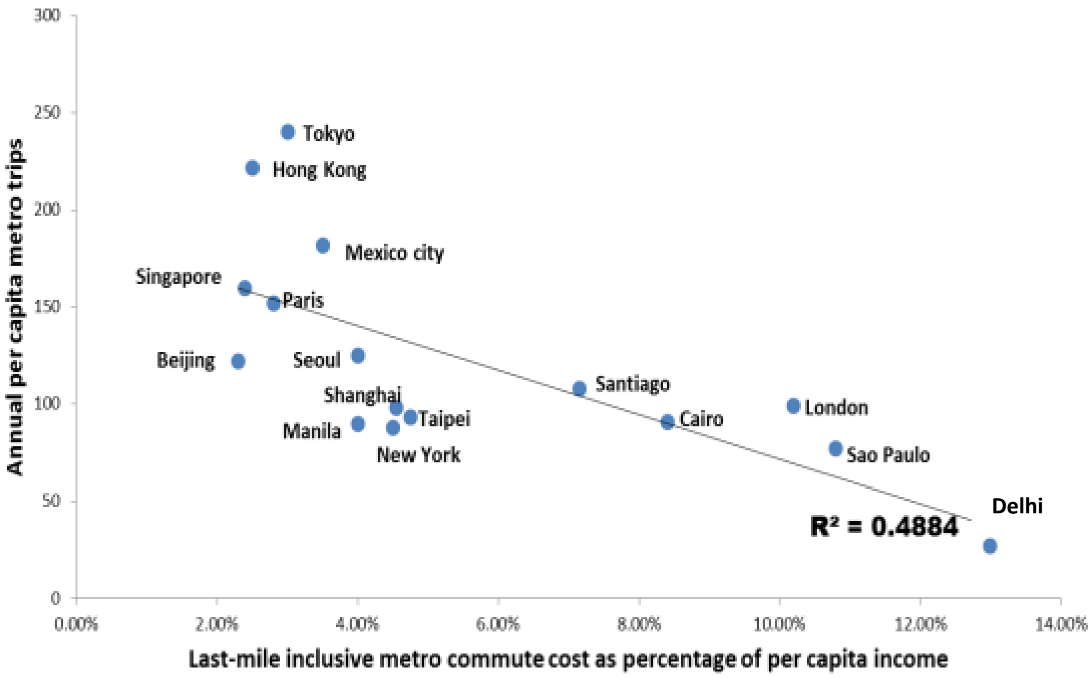


Figure 45 Metro Ridership and Affordability of Last-mile Inclusive Fares

(Source: (Mohan 2008, Babalik-Sutcliffe 2002, DMRC 2012, Cheong and Toh 2010, Wikipedia n.d., Tokyo Metro n.d., MTR n.d., Cairo Metro n.d., Metro de Santiago 2012, Metro Taipei n.d.), taking the fares for the dominant non-walk last-mile mode for each city; Delhi: autorickshaw; Singapore, London, Seoul, Beijing, Shanghai, New York, Taipei, Satiago, Cairo, SaoPaulo, Hongkong : feeder bus; Tokyo, Paris : Cycle; Mexico city, Manila: minibus/para-transit)

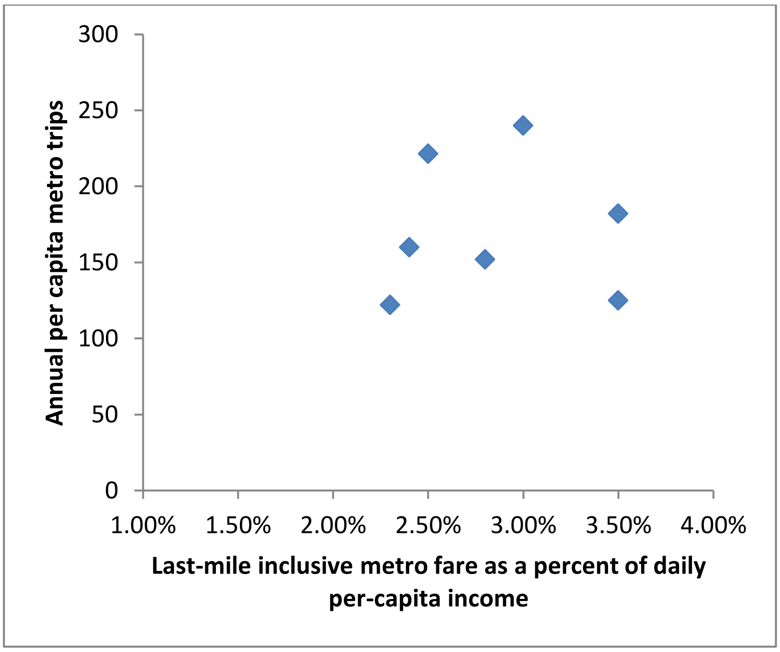


Figure 46 Cities with Low Last-mile inclusive Metro fares

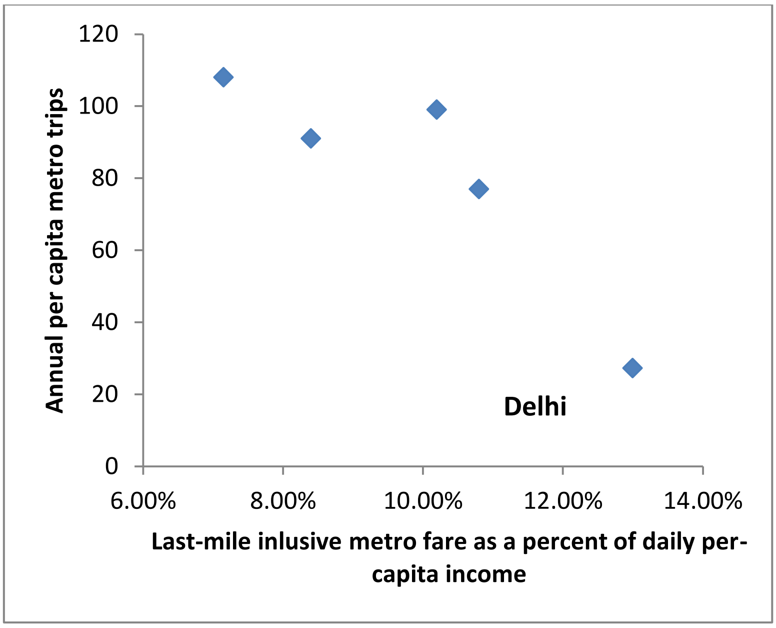


Figure 47 Cities with High Last-mile inclusive Metro Fares

Further break-up of **Figure 45** into cities with low and high last-mile-inclusive metro cost, as shown in **Figure 46** and **Figure 47**, suggests that a relationship between ridership and last-mile inclusive metro fare exists mainly for the cities where a large percentage of income has to be spent on the last-mile-inclusive metro commute. In other words, any small change in the last-mile fare or metro fare is more likely to have a negative impact on the metro ridership in the cities where a relatively large percentage (roughly more than 5-6%) of per-capita income is spent on commuting.

Prima facie, a costly last-mile appears to be a key reason for longer trip lengths and low-ridership on Delhi metro. To test this hypothesis and to understand the reasons for low ridership, a large commuter survey, having questions related to the last-mile, was conducted in 2012 along the problematic lines 5 and 6 of Delhi metro.

Data Analysis: Survey Findings

More than 10,000 commuters (metro users as well as non-users) living or working within a 1.5 km radius around 30 stations were surveyed on lines 5 and 6 of Delhi metro. Stratified random sampling was done for the survey wherein 360 commuters were picked for each station: 60% of the respondents were chosen from the area within 0.8 km radius around metro stations, while the other 40% lived within 0.8 km to 1.5 km around metro stations. Apart from gathering personal information like age, occupation and education, the respondents were asked questions like reasons for not riding metro (if they use some other mode), last-mile mode (if they ride metro) and metro trip length (origin and destination metro stations). The proportion of households and commercial establishments was maintained in the survey as per the actual distribution, however, the individual household or commercial unit was picked up randomly. The questionnaires were filled by interviewing the commuters. Some data (like education) was cross-checked with the respective organization (questionnaire in Appendix 'B').

Figure 48 shows the reasons for not riding metro as indicated by the surveyed commuters (multiple responses permitted). Last-mile related reasons like lack of feeder transport, lack of parking at stations and distance to station add up to more than 63% of all responses. Thus, the survey results corroborate the essential role of last-mile factors in metro ridership.

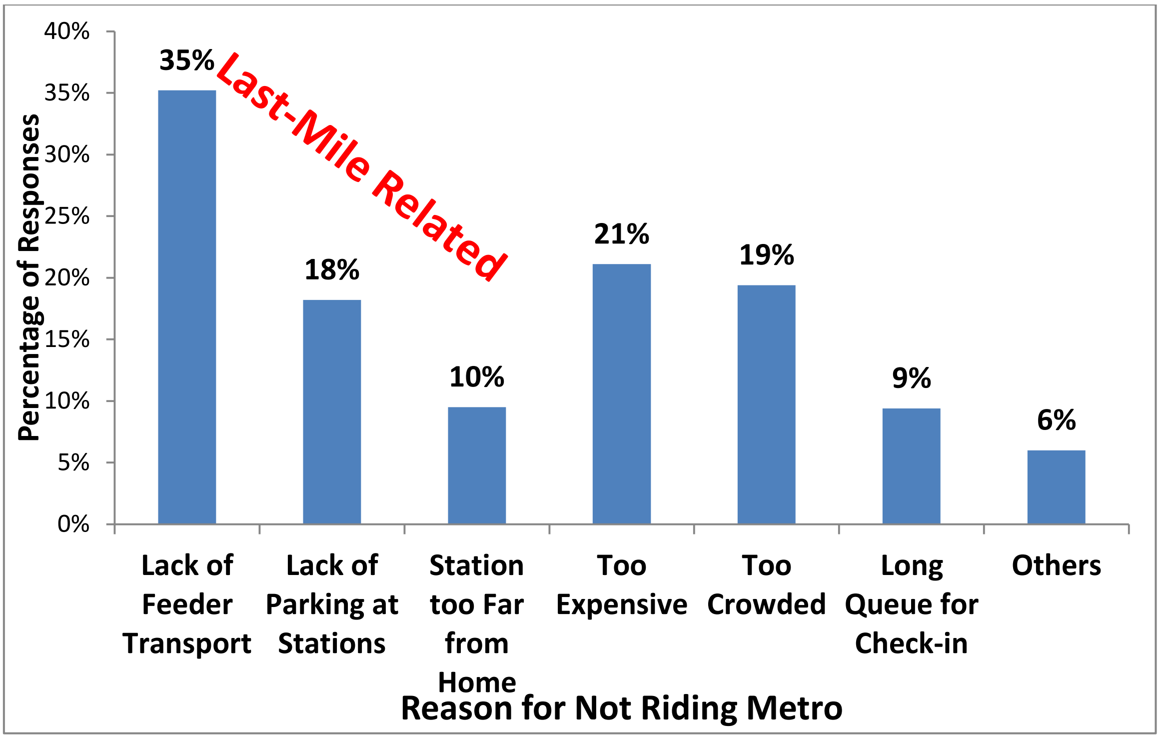


Figure 48 Survey Results: Reasons for Not Riding Metro

Figure 49 shows that commuters, in general, avoid use of multiple modes as less than 20% use two or more modes for commuting. As use of metro rail invariably involves use of a last-mile mode for commuters not living within walking distance of the stations, this paper focuses on various aspects of the last-mile access that may have an impact on metro ridership.

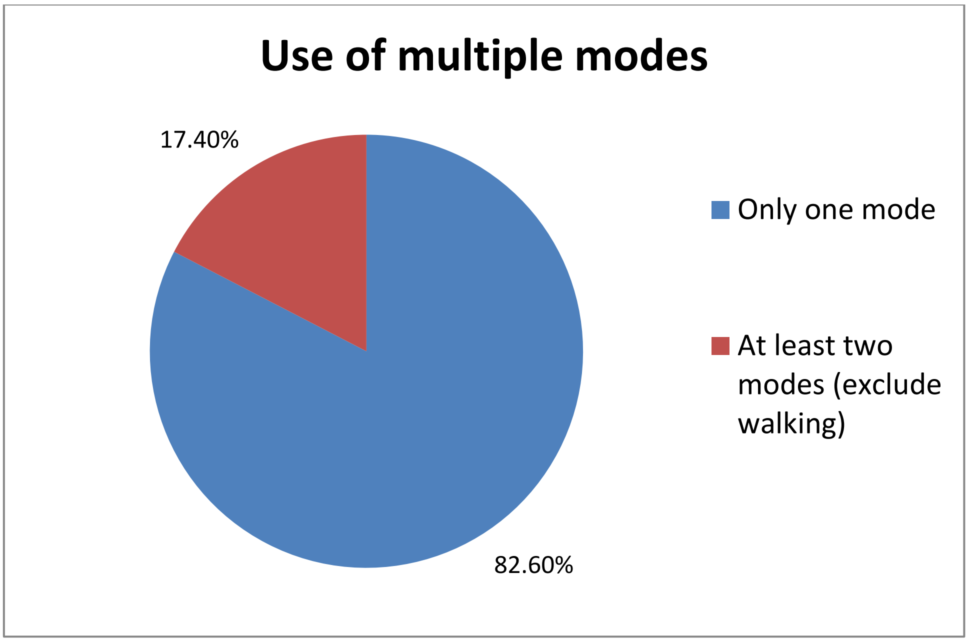


Figure 49 Multimodal Trips by Surveyed Commuters

Figure 50 shows the estimated modal split for the last-mile access to Delhi metro in 2012. Apart from a survey of metro commuters, we use feeder bus ridership data and parking census data for metro stations to estimate modal split for the last-mile. Almost two-third of all metro commuters either walk or are dropped off using a private or public (long-distance) vehicle for the last-mile.

Para-transits (auto-rickshaw, cycle-rickshaw and e-rickshaws) are the most widely used non-walk modes for the last-mile trips. Auto-rickshaw and cycle-rickshaw carry one person/family at a time, while e-rickshaw is a shared mode, carrying up to 6 persons in one trip. Rest of the modes; like feeder buses, cycle and park-and-ride; support less than 7% of all metro trips. DMRC operates a skeletal feeder bus service at 12 metro stations with around 100 mini-buses, running on just 15 routes (DMRC 2013). This service is used by less than 3% of metro users.

Another 3.5% of commuters use private cars and motor-bikes which are parked at the metro stations. However most of the metro stations invariably run out of parking space for cars during peak commuting hours. Use of cycling for the last-mile trip is insignificant, with around 0.5% commuters opting for it.

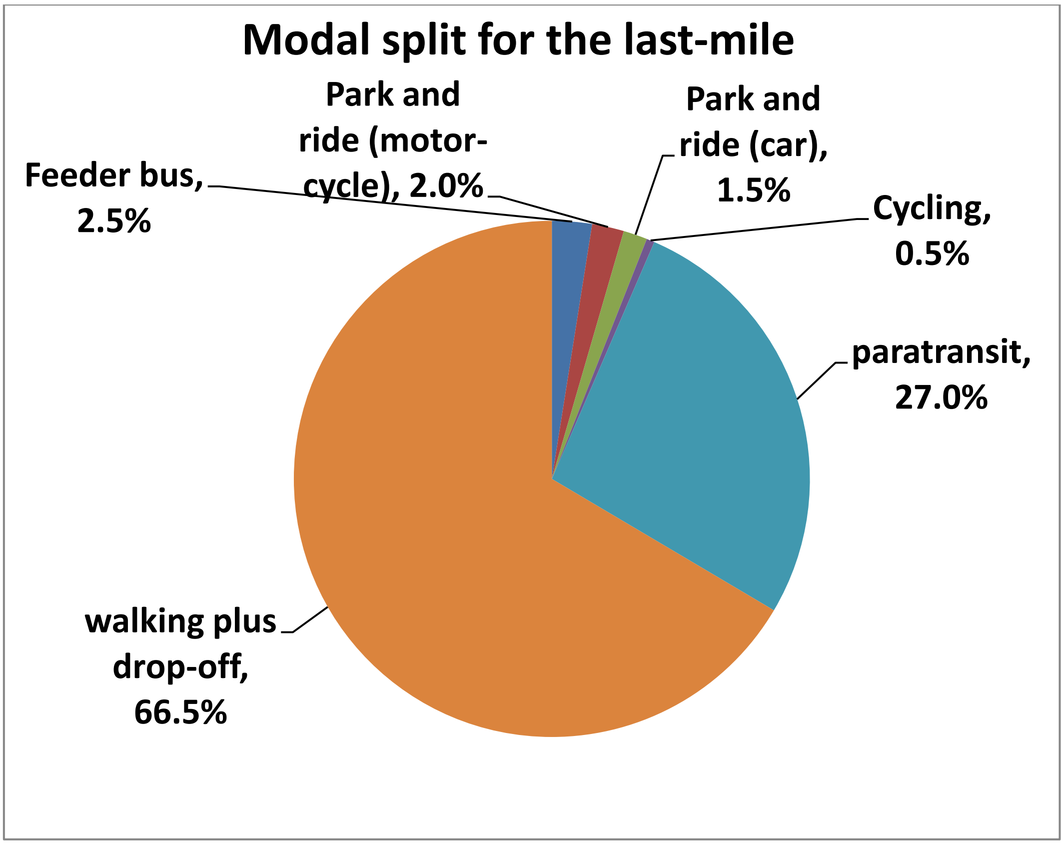


Figure 50 Modal-split for Last-mile on Delhi Metro (All Lines)

(Source: (DMRC 2012, DMRC 2012, Advani and Tiwari, Evaluation of public transport systems: case study of Delhi Metro 2005, Gupta and Agarwal 2008), para-transits include cycle-rickshaw and auto-rickshaw)

Figure 51 compares the cost for a return journey by metro (including two last-mile trips) for different last-mile modes. Feeder bus is the third cheapest last-mile mode after walking and cycling. However, the modal shares of cycling and feeder buses are very small as shown inFigure 50. Auto-rickshaws and cycle-rickshaws, which are the most widely used last-mile modes (exclude walking), are almost 3 times as costly as feeder buses. Shared e-rickshaw is a new mode that started in 2012 and is getting quite popular due to its low fares. Park and ride (car) is the costliest option and also faces capacity constraints at most of the stations.

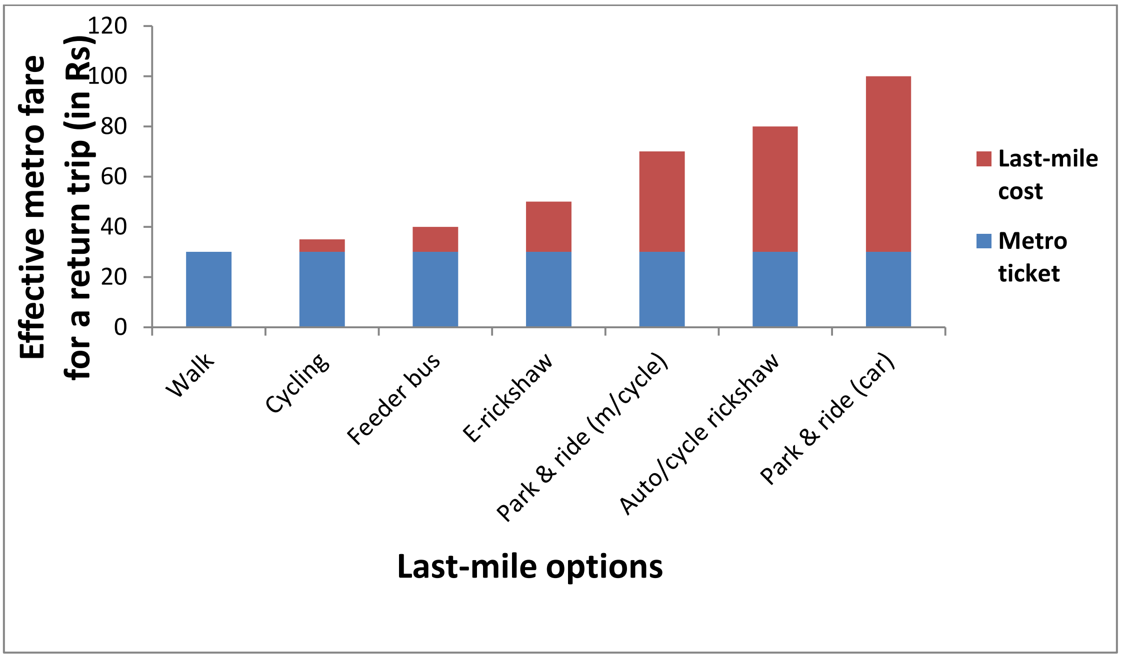


Figure 51 Effective Metro Fare with Different Last-mile Modes

(Assumptions: Metro return trip Fares for 15Km distance; all last-mile costs/fares assume 1 km distance; parking(8hr), amortization (10 years for car and motor-bike) and operation/maintenance cost approximated for the car and motorcycle models with the highest sales in Delhi)

A comparison of modal split for the area within 0.8 km radius (**Figure 52**) of a station, with the area (annulus) between 0.8 km and 1.5 km radius (**Figure 53**) from the same station, (taken together for all the 30 stations) shows a steep decline in the modal share of metro from 63% to 19%, while the corresponding modal share of bus rises from 25% to 48% . It indicates that last-mile accessibility has a large impact on metro ridership. Modal share of auto-rickshaw increases from 2% to 7% as the distance from the station increase, indicating its increasing use as a last-mile mode.

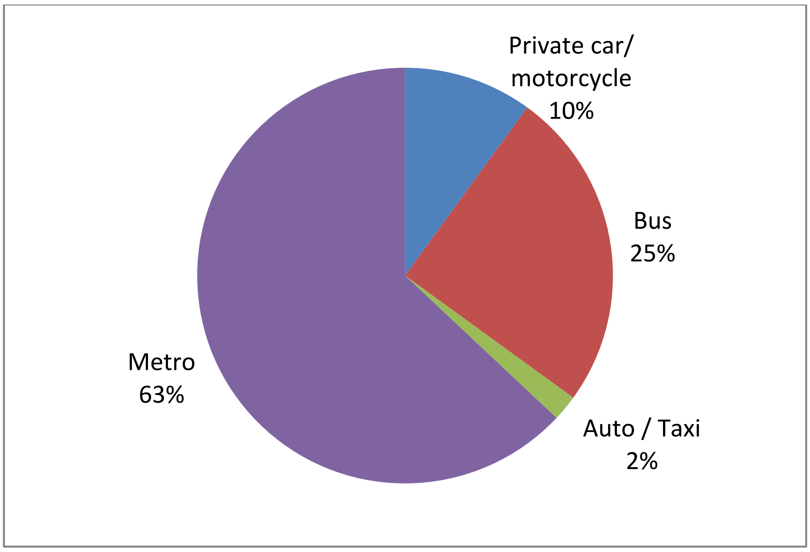


Figure 52 Modal Split within 0.8 Km Radius of Surveyed Stations

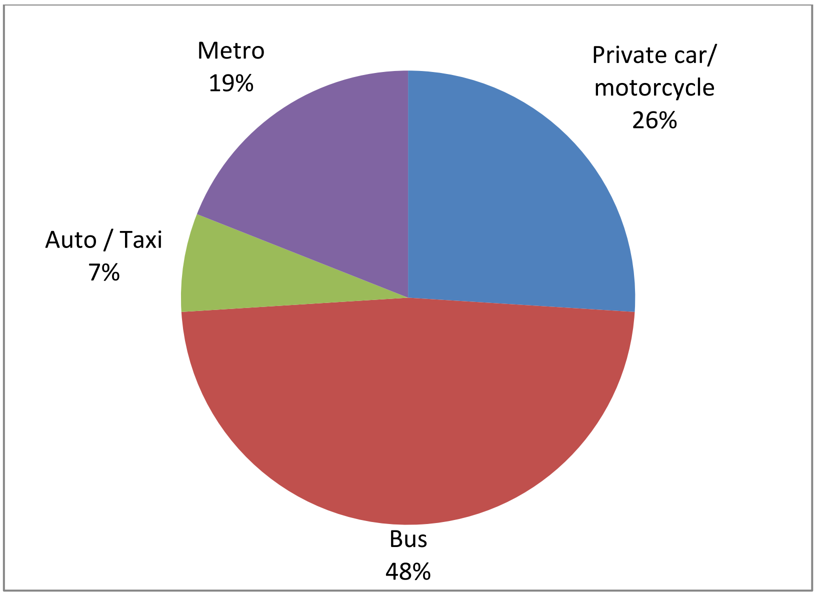


Figure 53 Modal Split in 0.8 km to 1.5 km Annulus around Surveyed Stations

A comparison of the percentage of metro commuters taking a non-walk last-mile trip and corresponding metro modal share for Lines 5 and 6, as shown in Figure 54, also suggests that the modal share of metro increases with an increase in usage of non-walk last-mile modes.

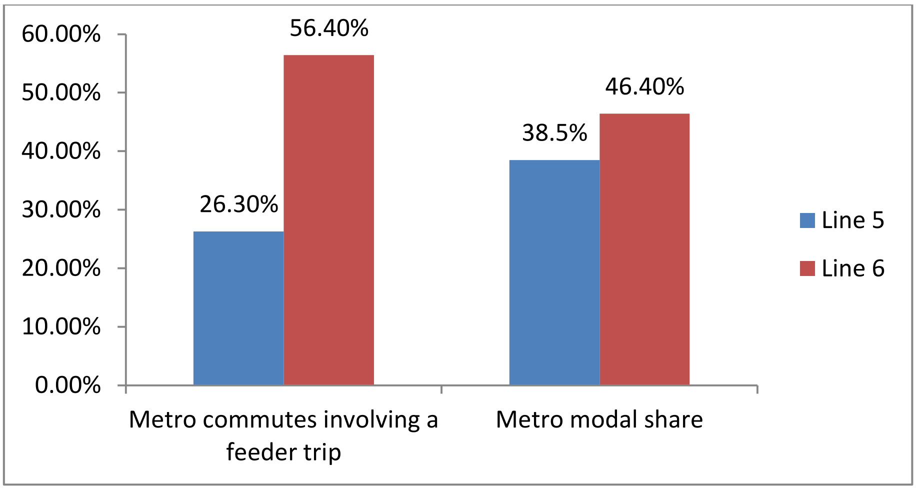


Figure 54 Non-walk Last-mile Trips and Metro Usage on Lines 5 and 6

We draw some more insights about the last-mile characteristics and metro ridership by plotting station-wise average values of various variables for the surveyed stations.

Last-mile usage and metro ridership

Metro ridership should increase with an increase in the effective catchment area of the stations. An increase in non-walk last-mile trips to a metro station indicates that more commuters living farther from the station elect to use metro services. Hence, we draw a scatter plot between the percentage of metro commuters making non-walk last-mile trips to a station and overall modal share of metro around that station, as shown in **Figure 55**.

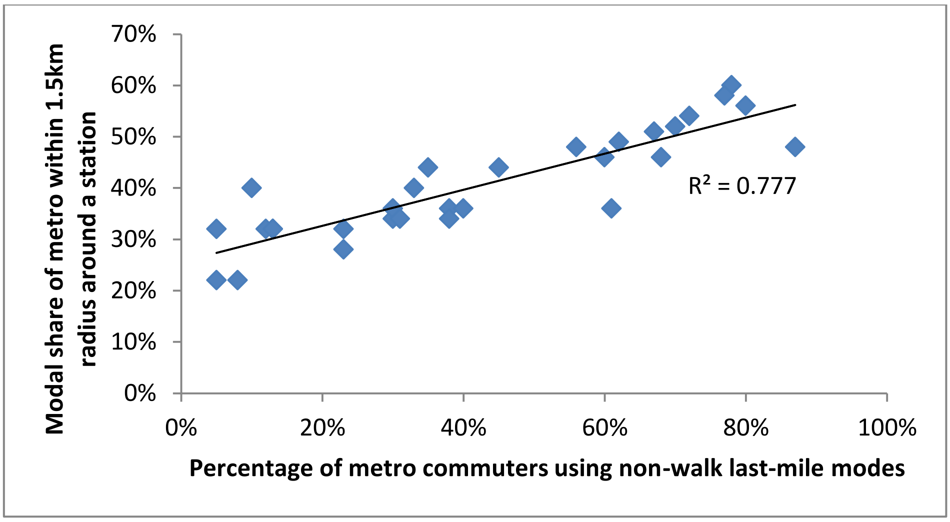


Figure 55 Last-mile and Metro Modal Share

In **Figure 55**, each of the 30 points on the graph represents the average of 360 responses collected for a metro station. We find that metro modal share is positively correlated (r =0.88, p= 0.01) with the use of non-walk last-mile modes. Though the causality can't be ascertained through statistical methods, the relationship suggests that metro ridership can be increased if more commuters could access and afford non-walk last-mile services.

Commuter income and Last-mile usage

In Delhi, with low income levels and relatively high fares for last-mile services, a large number of commuters may not be able to afford a metro commute due to a costly last-mile. We use university degree (education) as a proxy for income as many employers/households were not willing to disclose their incomes and it was easier to get the education data especially from the commercial establishments. University education can be taken as a good proxy for income in Delhi (Filmer and Pritchett 2001). In **Figure 56** We make a scatter plot between percentage of metro commuters with a university degree and non-walk last-mile users (r = 0.77, p=0.02) for each of the thirty stations by taking average of 360 values for each station.

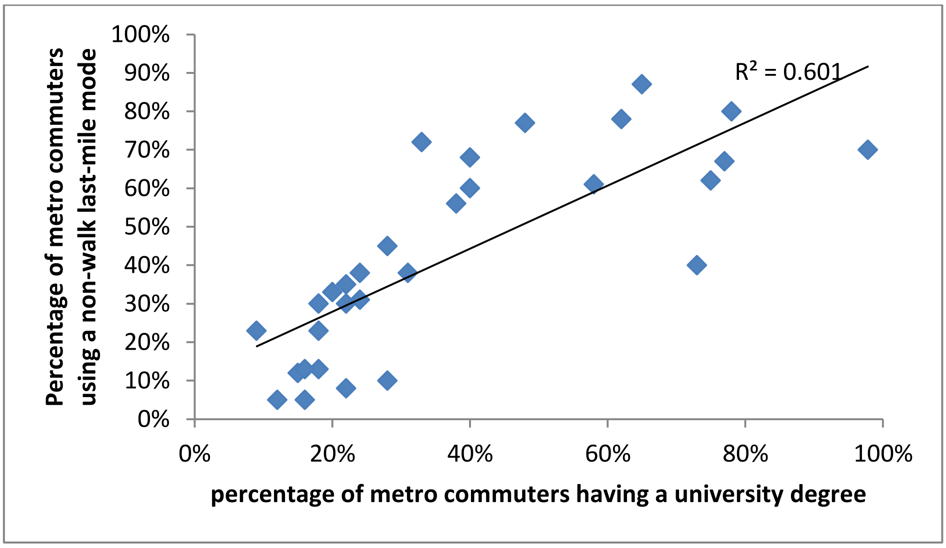


Figure 56 Education Level and Last-mile

Figure 56 shows that commuters with a university degree (implying above average incomes) are more likely to use the existing last-mile services and vice-versa. Hence, it suggests that a large fraction of low-earning commuters are sensitive to the cost of last-mile services. In other words, the demand for metro services is price elastic with respect to the last-mile inclusive price of metro usage and not just the metro fares. Hence, low-cost last-mile options should be encouraged to bring in more commuters to metro. Even partial subsidy to last-mile feeder operations by the metro operator might be a financially viable policy as increase in total revenue due to higher metro ridership should more than offset the subsidy on the last-mile.

Metro trip length and Last-mile usage

As last-mile services are relatively costly and unreliable in Delhi, commuters are less likely to use metro for short trips as overall travel time saving (metro vis-à-vis other modes) for short distances may not be able to offset the extra time taken, money spent and inconvenience caused by the last-mile services. In other words, commuters would make non-walk last-mile trips mainly for longer metro trips. We draw a scatter plot between the ‘percentage of metro trips more than 15km’ and the ‘percentage of metro commuters taking a non-walk last-mile mode’ (**Figure 57**).

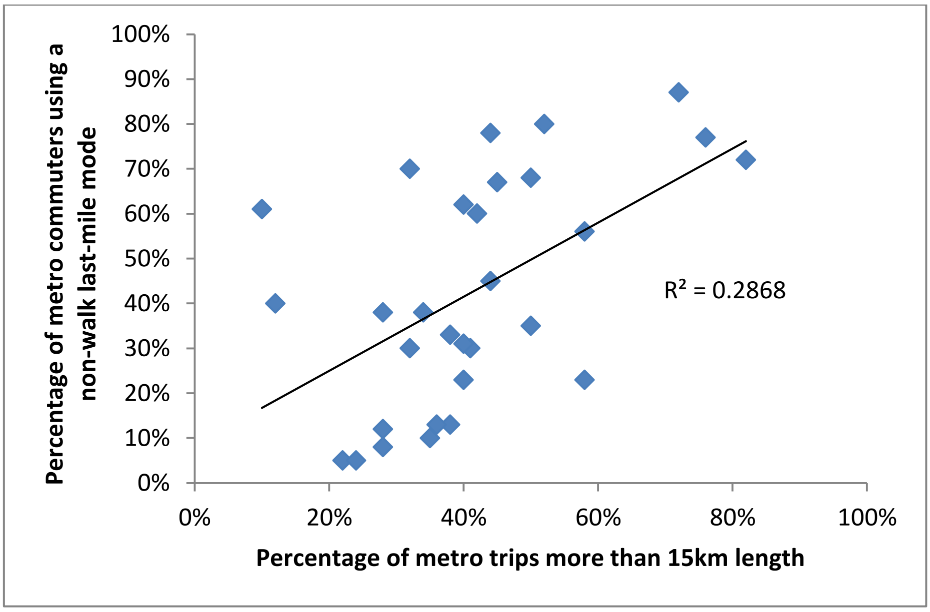


Figure 57 Metro Trip Length and Last-mile

Though, the trip distance is positively correlated with the last-mile service usage, we find that the relationship is statistically weak ($r = 0.53$, $p=0.14$). Nevertheless, the trend suggests that a reduction in the last-mile cost and improvement in efficiency of last-mile services may encourage more people with shorter commute distances to switch to metro.

Land-use and Last-mile services

The literature suggests that demand for last-mille services is low at the work-end of the commuting trip as compared to the home-end (Brunsing 1997, Kumar, Nguyen and Teo 2014). If this holds good for the case of Delhi metro, demand for the last-mile services should be higher around stations with a large residential land-use. In **Figure 58**, we make a scatter plot of residential land-use percentage vis-à-vis percentage of commuters using a last-mile service.

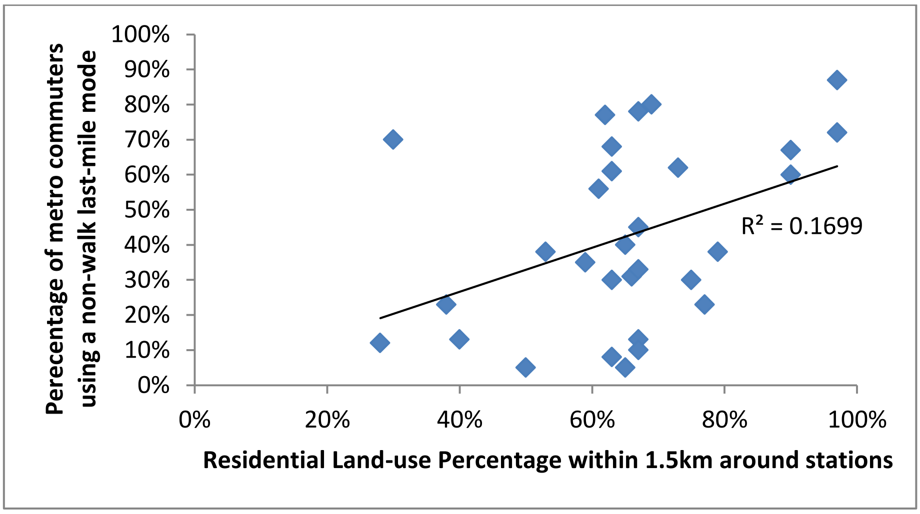


Figure 58 Land-use and Last-mile

Although there is a very weak positive correlation (r =0.41, p= 0.18) between residential land-use and usage of non-walk last-mile mode, yet it suggests that the residential pockets, especially in suburban areas, should get more attention for improving last-mile access as inter-station distances are large and metro network density is much low in suburban areas.

Policy Analysis and Recommendations

In this section, we examine the last-mile related policies in Delhi and make recommendations in view of the above findings/insights.

Feeder Buses

DMRC is designated by Government as the sole authority responsible for providing feeder bus services to metro stations. However, DMRC has provided only a skeletal feeder bus service confined mainly to high demand areas. Project reports for Delhi metro (Phases 1 and 2) recommended an elaborate feeder bus system comprising of 1500 buses on 293 routes (RITES

2005). However, till June 2013, only 130 buses were operating on 14 routes. Delhi metro is planning to increase the number of buses to 400 by July 2014. DMRC has divided bus routes into a few clusters and selects the bus operators through a competitive bidding process. The bus operators are responsible for procuring, operating and maintaining buses. DMRC helps the operators to buy buses through an advance payment which is recovered with interest over the concession period. Hence, effectively no subsidy is given by DMRC for feeder bus operations. DMRC fixes the fares as a part of the contract with bus operators.

The policy of DMRC is to make sure that feeder services are financially viable. On account of this principle, there is gross underinvestment in feeder buses. Other agencies or private players cannot operate more feeder services on their own unless they obtain authorization to do so. We highlight in our analysis that feeder buses are one of the cheaper options for last-mile connections. An increase in their numbers with current pricing or even a higher pricing should lead to a substantial increase in demand for metro services, thus leading to an increase in net revenues for the metro operator despite any subsidy/extra investment in feeder buses. An expansion of feeder services would make metro rail accessible and affordable to a larger segment of the population.

The reliability and frequency of bus services are very important. Hence, emphasis should be placed on providing smaller buses with high frequency services and few stops. Emphasis should be on improving feeder services in residential areas, as most of the commercial/office areas are closer to the metro stations and are generally well served by market-driven para-transits. The recent initiative by DMRC to enhance the bus fleet to 400 is a step in the right direction but more buses need to be introduced on new as well as existing routes as latent demand for feeder buses is high. DMRC should also implement fare integration and distance based charging between feeder buses and metro services in due course. Apart from passenger convenience, this would help in better assessment and targeting of subsidy on feeder buses.

Cycling for the Last-mile

The potential of last-mile cycling

More than half of Delhi's population lives in dense urban sprawl with narrow streets, where feeder bus services would have limited reach. Cycling can be an efficient and flexible last-mile solution under such conditions. Though cycling is still widely used in Delhi for end-to-end trips with a modal share of more than 5%, its use for the last-mile is very low at around 0.5%. Most of the cyclists in Delhi are 'captive' travellers who cycle because they cannot afford any other mode. As they cannot afford metro fares either, they continue to use the bicycles for their commuting trips. On the other hand, many metro users, who may find cycling an efficient option for the last-mile, shun bicycles mainly due to the lack of infrastructure for safe cycling.

Though a cycling master plan for Delhi was prepared in 1998 (Tiwari 1999), no action was taken to implement it (Sahai and Bishop 2010). In a dense, low income sprawl like Delhi, cycling is one of the most efficient and sustainable modes for the last-mile. There is evidence from other cities to show that despite the challenges related to weather and social status, more commuters would cycle the last-mile if better infrastructure and facilities were provided

(Buehler and Pucher 2010, Conway 2012, Heinen, Wee and Maat 2010, Pucher, Dill and Handy 2010).

DMRC has taken many initiatives to promote last-mile cycling like providing free parking, bike-rental shops and bike-sharing service (DMRC 2012). These initiatives were not particularly successful and were discontinued at most of the stations, except for the Vishwavidyalaya station where a bike-rental service is still in operation due to high demand from the Delhi university students. The research literature suggests that the main reason for poor response to these initiatives is a lack of safe cycling infrastructure around the target stations (Mohan 2008, Advani and Tiwari 2005). Unless opportunities for safe cycling are created, commuters with a 'choice' will not cycle.

Cycling policy recommendations for last-mile

Targeted infrastructure should be developed around metro stations to encourage the choice of cycling for last-mile transport. To begin with, infrastructure like dedicated cycling tracks, separated cycling lanes and cycle-friendly intersections should be developed in residential suburban towns where the number of last-mile trips would be high and it should be relatively easier to secure the necessary land. Facilities for cyclists like secure parking and maintenance shops should be developed at the stations.

Promotion of pedelecs[9] as bicycles, with permission to use cycling infrastructure, could help in encouraging a switch from motorcycles to pedelecs for the last-mile, as well as for end-to-end trips. Pedelecs have become quite popular in countries like China, Japan and Germany. The safety

[9] Pedal-assisted electric bikes with speed regulation.

aspect of these bikes would not be a problem with maximum speed regulation at the manufacturing stage (Weinert, Ma and Cherry 2007).

More than 50% of Delhi's population lives in unauthorized colonies and/or slum clusters. Municipal authorities could leverage the regularization process for unauthorized colonies to promote last-mile cycling. Cars could be kept out of these colonies, with typically narrow streets, through physical provisions like bollards. Cycling infrastructure should be developed to link these colonies with metro stations.

DMRC could also experiment with concessions in metro fare for commuters using cycling as a feeder mode. This could bring in the commuters who are presently unable to use metro due to a costly last-mile service coupled with high metro fares.

Para-transits

Cycle-rickshaw and auto-rickshaw

Though quite costly, cycle-rickshaw and auto-rickshaw are the most widely used non-walk last-mile modes in Delhi. These are market-driven services, provided by individual private operators with minimal regulation. Some pricing and safety-related regulation of the auto-rickshaws exists but is not very effective. Cycle-rickshaws are banned from operating in certain areas. Otherwise there is practically no regulation of their operation, fares and parking. Despite problems related to reliability and overcharging, these para-transits play an important role in providing market-driven last-mile services. However, government should facilitate and effectively regulate some aspects of these services like parking, fares and safety. Many metro stations have earmarked parking space for these rickshaws but implementation is still poor.

E-rickshaw

E-rickshaws are battery operated shared rickshaws (tri-cycles) that can seat four passengers. It has emerged as a popular mode for the last-mile trips to metro stations over last two years. Number of e-rickshaws has grown exponentially to more than 100,000 since their introduction in 2012. It is a cheap, clean and easily manoeuvrable shared-mode. However, there are many regulatory issues related to its safety, speed and area of operation where the government is yet to come up with policy guidelines.

Delhi metro ridership has gone up by about one-third (from 1.8 million per day in May 2012 to more than 2.4 million per day in June 2014) since introduction of e-rickshaws in 2012. No new metro lines or stations were commissioned during this period. There was also neither any reduction in metro fares nor any significant development along the metro lines. Hence this increase in metro ridership may be largely attributed to the emergence of this cheap last-mile option. Government should encourage and regulate this mode of transport. It should promote entry of corporate entities in para-transits to improve the quality and reliability of services.

Park and ride

Park-and-ride services, especially for cars, play a very limited role in a dense city like Delhi. Presently all park-and-ride facilities are fully utilized during peak hours, still it caters to less than 3.5% of all metro trips. There is no scope for expansion of these facilities in city stations. Instead this valuable land could be better exploited for commercial purposes and the revenues could be invested to improve feeder buses and to build cycling/walking infrastructure around stations. Park-and-ride should be gradually limited to only suburban stations. Stations in the city should have parking only for bicycles, feeder buses and para-transits.

Walking Infrastructure

Delhi, in general, has poor pedestrian infrastructure. Places around metro stations are no exception. Despite poor and unsafe walking conditions, people living in the vicinity of metro stations manage to walk to the stations. However, improvements in pedestrian infrastructure like covered walkways, illumination and pedestrian signals could encourage commuters to walk relatively longer distances to metro stations, obviating the need for a motorcycle or feeder bus to reach the station.

Last-mile inclusive transit planning

As evident from the discussion, an improvement in last-mile infrastructure and services can increase transit ridership, but current transit planning does not include last-mile infrastructure plans. Though the project reports for Delhi metro make a detailed assessment about feeder buses, no financial estimation or provision was made in the plan/report (RITES 1998, RITES 2005). No planning is done for last-mile walking and/or cycling infrastructure. The haphazard development of last-mile infrastructure, almost as an afterthought after commissioning of metro stations, can result in many long-term problems and inefficiencies such as: engineering difficulties; higher cost of retrofitting; paucity of funds; and resistance to travel behaviour change with incremental improvements (Brunsing 1997, Krizek and Stonebraker 2010). Hence we suggest that last-mile walking, cycling and feeder bus infrastructure should be planned, financed and constructed as an integral part of a metro system. To begin with, a lump-sum amount, at around 10% of the project cost, should be earmarked for the last-mile investment. Further, we develop a simple model (a variant of knapsack problem), to make an optimal choice of last-mile investments for a given budget.

Optimization Model

We propose a simple binary linear model to choose an optimal portfolio of last-mile investment levels/ scenarios to maximize system-wide benefits.

- Let a metro system have *M* number of stations. As a base case, consider the metro system without any last mile investment : benefits (B_0), cost (C_0)

- For each station $j \epsilon M$, let iϵN be the set of last-mile investment levels with incrementally increasing last-mile infrastructure investments, for example:

  - For i=1: basic walking infrastructure around the station to residential/ commercial clusters within 500m radius
  - For i=2: covered walking infrastructure around the station to residential/ commercial clusters within 500m radius
  - For i=3: Covered walking infrastructure around the station to places with in 500m radius plus cycling lanes/tracks to residential/ commercial clusters within 1.5 km radius
  - For i=4: Covered walking infrastructure around the station to places with in 800m radius plus cycling lanes/tracks to residential/ comercial clusters within 1.5 km radius

- For i=5 : Covered walking infrastructure around the station to places with in 800m radius plus cycling lanes/tracks to residential/ commercial clusters within 3 km radius
- And so on..

- Let c_{ij} and b_{ij} be the extra cost and benefit respectively (w.r.t. the base case B_0 , C_0) for the last-mile investment level i at the station j
- Let x_{ij} be the binary variables, x_{ij}=1 if level i is invested at station j
- Choose maximum one investment level $i\epsilon N$ for each station $j\epsilon M$ such that it maximizes the system-wide last-mile benefits $\sum_{j\in M,i\in N} b_{ij}x_{ij}$ subject to the constraints:
  - $b_{ij}x_{ij} \geq c_{ij}x_{ij}$ for each station $j\epsilon M$
  - $\sum_{j\in M,i\in N} c_{ij}x_{ij} \leq M_B$ where M_B is the maximum budget for last-mile works
  - It can be formulated and solved as a binary linear programming problem

Table 3 Optimization Model

Objective function: Maximize System-wide benefits	$\sum_{j\in M,i\in N} b_{ij}x_{ij}$	
Viability constraint	$b_{ij}x_{ij} \geq c_{ij}x_{ij}$	$\forall j \in M, \forall i \in N$
Budget constraint	$\sum_{j\in M,i\in N} c_{ij}x_{ij} \leq M_B$	
Binary choice constraint	$x_{ij} \in \{0,1\}$	$\forall j \in M, \forall i \in N$
Not more than one last-mile level for each station	$\sum_{i\in N} x_{ij} = 1$	$\forall j \in M$

This model makes optimal choice of last-mile portfolio for a given budget. It can also compute budget requirement for maximizing benefit on removing the budget constraint. We solve this model for a hypothetical metro system having 7 stations with 5 last-mile scenarios for each station. The assumed inputs (benefits and cost matrix) are shown in **Table 4** and **Table 5**. We also approximate an optimal budget by removing the budget constraint. Solutions of the model for different budgets as well as optimal budget requirement are shown in Table 6. This model is simple to formulate and can be solved using any commercial solver.

Table 4 Benefits Matrix (in Million $)

Last-mile level→	Level 1	Level 2	Level 3	Level 4	Level 5
Station A	10	12	13	14	15
Station B	2	5	8	16	17
Station C	2	9	10	12	17
Station D	3	4	12	13	14
Station E	1	4	7	10	15
Station F	3	7	10	15	17
Station G	1	6	9	11	24

Table 5 Cost Matrix (in Million $)

Last-mile level→	Level 1	Level 2	Level 3	Level 4	Level 5
Station A	4	9	11	15	22
Station B	3	6	9	14	20
Station C	2	4	8	13	18
Station D	2	5	7	12	17
Station E	2	5	8	11	16
Station F	3	7	10	15	17
Station G	2	5	6	12	15

Table 6 Solution: Last-mile Levels for Different Budgets, Optimal Budget

Last-mile budget→	20 million $	40 million $	60 million $	70 million $	Optimal Budget
Station A	Level 1	Level 1	Level 3	Level 1	Level 3
Station B	-	Level 4	-	Level 4	Level 4
Station C	Level 2	Level 2	Level 3	Level 3	Level 3
Station D	Level 3	-	Level 3	Level 3	Level 4
Station E	-	-	-	-	-
Station F	-	Level 1	Level 5	Level 5	Level 5
Station G	Level 2	Level 5	Level 5	Level 5	Level 5
Total benefits	37	62	76	83	**93**
Actual Investment	20	40	58	63	**77**

Chapter Conclusion

In this chapter, we study the impact of last-mile services on metro ridership in Delhi. It brings out the fact that a costly and inefficient last-mile service may make metro services uncompetitive for a large section of commuters, especially in low-income developing cities. The survey data from Delhi helps in drawing insights about the nature of required last-mile services and funding possibilities. The study suggests that the funding of last-mile feeder buses by metro operators can be a financially viable proposition.

Based on the insights from this study, we suggest that detailed last-mile planning and investment should be included as an integral part of a metro project to increase its ridership and consequent economic benefits. We also propose a simple model/approach to choose an optimal portfolio of last-mile investment options for a metro rail network.

However, it is vital to measure the last-mile accessibility in order to improve it. In the next chapter, we propose an approach to measure last-mile accessibility in a comprehensive manner through a combination of indices.

Chapter-5
Last-Mile Indices: An Approach to Measure Accessibility of Transit Stations

Introduction

An increase in the ridership of mass transits can help in alleviating traffic congestion on roads. However, to compete successfully with cars and motor-cycles, public transport must strive to provide a door-to-door service to commuters. Hence, easy access to transit stations from homes and workplaces (last-mile) becomes very important. Last-mile access should be efficient, cheap and comfortable (Givoni and Rietveld 2007, Rietveld 2001).

There is a large body of evidence suggesting that poor last-mile access is a key factor affecting mass-transit ridership (Cervero and Golub 2011, Cheong and Toh 2010, Krizek and Stonebraker 2010, Kumar, Nguyen and Teo 2014) . Lack of good last-mile infrastructure is the result of a systemic malaise in the urban transport planning which is based largely on aggregate flows. Nevertheless, with increasing realization of the importance of last-mile access, some cities have started planning for feeder bus services along with a metro rail system. However, other efficient and cheap modes for last-mile access like walking and cycling are still largely neglected. One of the reasons for neglect is a lack of benchmarks for the last-mile access.

It is important to have indicators to measure, benchmark and improve the state of a system. Presently, there is no comprehensive way to assess the last-mile access to metro rail stations. We take a systems perspective to develop tools for assessing the last-mile accessibility of metro stations. In simple terms, we understand and examine how different last-mile modes should be developed and dovetailed in different contexts to offer a comprehensive last-mile solution.

In this chapter, we develop indices to measure last-mile accessibility of transit stations through individual modes as well as through their actual or desired combinations. These indices can be a useful tool for planners to set policy goals for the last-mile access and to figure out ways of achieving it.

The ease of walking and cycling in an area are often termed as walkability and bikeability respectively. In the literature, there exist many indicators to measure walkability and bikeability of an area. However, these indicators are mostly context specific and lack a focus on accessibility to transit stations. We cover some of the latest and relevant developments in the literature survey.

Literature survey and Motivation

The World Bank proposed a Global Walkability index to compare safety, security and convenience of the pedestrian environments across different cities in the world. This index is meant for inter-city comparison and measures average walkability in a city through a random sample of streets. The combined walkability index value ranges from 1 to 20 with 20 corresponding to the best conditions for walking. The index value is the weighted average of the respective values for five variables related to safety, convenience, security, health and policy with corresponding weights as 30%, 30%, 20% 10% and 10% respectively (World Bank 2008).

Frank and Sallis (2010) developed a GIS-based walkability index from the neighbourhood quality of life perspective to measure the impact of urban form on walkability. Urban form is characterized based on land-use mix, street connectivity, residential density and commercial density (retail shops) (Frank, et al. 2010). This index is sum of z-scores of four urban form measures with street connectivity having double the weight of the other three variables.

There are also efforts by a company called Walk Score to come up with the indices like Walk score, Bike score and Transit score to measure ease of access to various amenities like businesses, parks and schools through various modes (Walk Score 2014). These scores range from 0 to 100. These indices are meant primarily for use by real-estate companies. Olszewski et al (2005) use equivalent walking distance to assess accessibility of MRT stations in Singapore, however, they don’t develop it into an index (Olszewski and Wibowo 2005).

Winters et al (2013) developed a bikeability index for Vancouver area based on five factors: bicycle facility availability; bicycle facility quality; street connectivity; topography; and land use. Opinion surveys, travel behaviour studies and focus group discussions were conducted to choose these factors and their relative weightage in the index (Winters, et al. 2013). They also developed GIS-based bikeability surface for the region as a useful visual tool to figure out areas for improvement.

An index called ‘BikeBR’ was developed to measure bikeability in the city of Baton Rouge. This index tries to measure safety, ease and desirability of cycling in an area and is based on three composite factors: bicycle facilities, street connectivity and residential density (BikeBR 2012). However, none of the bikeability indices tries to capture the ease of a transit station access by cycle from its catchment.

A few indices related to public transport access also exist. Ryus et al.(2000) developed a Transit Level of Service (TLOS) index for the state of Florida which tries to measure safety and comfort of pedestrian routes to transit stations besides the frequency of transits (Ryus, et al. 2000). Rood (1998) proposed indices called 'Regional Index of Transit Accessibility' (RITA) to measure accessibility of people from their residences to workplaces, commercial areas, hospitals etc. within a city region using transit; and 'Local Access of Transit Availability' (LITA) to measure transit service intensity/ availability across metropolitan areas. These indices try to capture availability and comfort of transit service besides measuring land-use intensity and walkability in vicinity of stations with a broader objective to promote transit oriented development. RITA makes a comparative measurement of accessibility by transit and automobile in terms of time and comfort, while LITA scores factors like route coverage, frequency and capacity of transits (Rood 1997).

Bhat et al. (2006) developed a 'Transit Accessibility Measure' (TAM) for use by Texas department of transport (TxDOT). This index comprised of two sub-indices called 'Transit Accessibility Index' (TAI) and 'Transit Dependence Index' (TDI). TAI is based on components of transit level of service like frequency, capacity and network density while TDI tries to measure dependency of the potential commuters on transit service through their socio-demographic profile (TxDOT 2006).

One of the most popular indices for public transport access is the 'Public Transport Accessibility Level' (PTAL) developed and used by Transport for London (Transport for London 2010) . It is a much simpler index as compared to American indices like TAM. The PTAL ranks areas/points of interest in London from 1 to 6 based on the effective access time to the nearest public transport. It measures walking time from a point of interest to the nearest public transport stop/station, reliability of the service, number of services available within the catchment and the average waiting time. It considers all public transport modes and does not take into account quality of service like crowding and travel time. This index is used for public transport improvement, parking requirements and land-use planning in London. Many other cities in UK as well as in Australia and New Zealand have also adopted PTAL.

However, there is hardly any research to measure the last-mile access to mass transit stations through different modes like walking, cycling and feeder buses individually or on the overall effect of different last-mile modes on the accessibility of the stations . There does not exist any index to capture the accessibility of transit stations through a combination of different modes. The proposed Last-mile index and its constituent sub-indices provide a holistic perspective of the last-mile accessibility along with the tools for a more localised, mode-wise analysis.

Different modes for last-mile access and the factors affecting their level of service (LOS) were chosen based on a study of existing theoretical and empirical studies. We chose to study walking, cycling, feeder buses and shared para-transits as the main last-mile modes. We picked walking, feeder buses and shared para-transits due to their widespread use in the cities we studied, while cycling was selected as it is desirable from a policy perspective to promote last-mile cycling on account of its efficiency and affordability.

The objective of this work is to develop indices to measure the level of service (LOS) of the chosen components of the last-mile access i.e. walking, cycling and feeder bus/shared para-transit.

In chapter 3 and 4, through case studies of Singapore and Delhi, we find that most of the commuters choose (or sometimes are forced) to walk or take a feeder bus/ shared para-transit for the last-mile. Very few commuters chose to cycle for the last-mile in these two cities. However, as mentioned earlier in chapter 2 and 3, cycling is a cheap and efficient option for short trips and many cities in Europe and China, with widely varying climatic conditions, have a large number of commuters using it for the last-mile. Hence, policy-makers should consider promoting cycling as an option for the last-mile in most cities. Therefore, we include an index for bikeability while trying to measure the quality of last-mile access.

Methodology and Data Collection

Methodology

As discussed above, we develop various indices to measure the ease of access to metro stations through different last-mile modes like walking, cycling and feeder buses. The catchment area of each metro station is marked using Voronoi diagrams with 3km radial distance as the upper limit in case of an unbounded cell. Each catchment is divided into 20 to 50 clusters of buildings based on the relative uniformity in last-mile access to the nearest metro station. In other words, buildings in the same cluster should have a common feeder-bus stop and should not have significant differences in walking and cycling access to the transit station.

To measure walkability and bikeability, we propose a concept of effective distance, taking into account comfort, safety and convenience by using various factors and penalties. We consider a scale from 0 to 100 with 100 corresponding to the accessibility level equalling or exceeding the minimum desired standards. We compute these indices for each cluster and finally take weighted average (based on populations) of all the clusters in the catchment of a transit station to assign index value to that station.

For feeder buses and shared para-transits, we propose a concept of effective time taken in reaching the transit station using a feeder services. It includes time taken for accessing bus- stop, waiting and traveling time along with a reliability factor. Here again, we consider a scale from 0 to 100 with 100 corresponding to the level of service (LOS) equalling or exceeding the minimum desired standards. We compute this index for each cluster and take the weighted average of all clusters for a station.

Next, we propose various indices and explain the methodology for their computation:

Last-Mile Walking Index (LMWI)

- Calculate the effective walking distance from a cluster to the station: first, divide the actual walking distance by safety and convenience factors; second, add penalty distances for unsignalled road crossings and Foot-over-bridges by 50 meter per lane and 100 meter per bridge, respectively (Frank, et al. 2010, Givoni and Rietveld 2007).
- Walking safety factor: very unsafe(0.25), unsafe(0.5), safe(0.8), very safe(1); based on weighted average of five variables: separate sidewalks, speed of vehicular traffic, lighting, retail spaces and security

perception with respective weights as 0.5, 0.2, 0.1, 0.1 and 0.1, respectively (Rood 1997, Transport for London 2010, TxDOT 2006).

- Walking convenience factor: very bad (0.5), bad (0.67), good (0.8)), very good (1); based on weighted average of five variables: width of walkways, shade, quality of walkway surface, waterlogging, cleanliness with respective weights as 0.5, 0.2, 0.1, 0.1 and 0.1 respectively.

  We take 800m (10 min walking time by taking 4.8 km/h as average speed) as maximum effective walking distance for a walking index of 100 (Rietveld 2001, Transport for London 2010)
- Last-mile walking index (LMWI) for a cluster = (800 / (effective walking distance in meters)) *100
- Upper bound for LMWI is 100

Last-Mile Biking Index (LMBI)

- Calculate the effective biking distance from a cluster to the station: first, divide the actual biking distance by safety and convenience factors; second, add penalty distances for unsignalled road crossings by 50 meter per lane and for gradients by increasing the respective distance by 50% for each percentage increase in the gradient beyond 2% (BikeBR 2012, Heinen, Wee and Maat 2010).
- Biking safety factor: very unsafe (0.25), unsafe (0.5), safe (0.8), very safe (1); based on weighted average of five variables: separate cycling infrastructure (segregated track, lane), speed of vehicular traffic, lighting, retail spaces and security perception with respective weights as 0.5, 0.2, 0.1, 0.1 and 0.1, respectively (Brunsing 1997, Martens 2007).
- Biking convenience factor: very bad (0.5), bad (0.67), good (0.8)), very good (1); based on weighted average of five variables: parking at stations, quality of cycling route (width, surface, shade), waterlogging and cleanliness, cycle repair shops and retail spaces with respective weights as 0.5, 0.2, 0.1, 0.1 and 0.1, respectively (Krizek, Barnes and Thompson 2009, Martens 2007, Winters, et al. 2013).

- Take 2500 m as maximum effective distance for a biking index of 100 corresponding to 10 min travel time taking avg cycling speed as 15 km/h (BikeBR 2012, Brunsing 1997, K. J. Krizek 2012)
- Last-mile Bike Index (LMBI)= (2500 / effective biking distance)*100
- Upper bound for LMBI is 100

Last-Mile Feeder Index (LMFI)

- Calculate the effective time taken in reaching the transit station using feeder bus and/or shared paratransit
- Effective travel time (in min) to transit station includes walking time to bus stop, waiting time for the feeder service, travel time in the feeder service and walking time to station from the drop-off point . We also include a reliability factor (value ranging from 1 to 10 min depending on reliability of schedule and over-crowding) (Krygsman, Dijst and Arentze 2004, Lee, Sun and Erath 2012)
- We take 15 min as maximum effective travel time for feeder bus or shared para-transit for an index value of 100.
- Last-mile Feeder Index (LMFI)= (15/ (effective travel time)) *100
- Upper bound for LMFI is 100

Last-Mile Index (LMI)

Last-mile Index (LMI) tries to measure last-mile accessibility from a normative policy perspective. It assumes that the commuters living/working within 500m radial distance from the stations should walk to the stations, while the commuters living beyond it will walk, bike or take a feeder bus depending on the distance from the station and the expected percentage of commuters opting to bike instead of taking a feeder bus. It assumes a linear variation in the modal share of walking from 100% to 0% as the radial distance from station increases from 500 m to 1500 m. Further, we assume that the ratio of modal shares of cycling and feeder bus would remain constant for distances between 500 and 1.5 km from the station. We call this the biking ratio (f). In our computations, we assume the biking ratio (f) as 0.2. Beyond 1.5 km distance, cycling's modal share is assumed to decline linearly to zero while the feeder bus modal share goes up as the distance increases to 3 km. The LMI for any cluster is a weighted average of the three indices (LMWI, LMBI and LMFI), where weights are assigned based on the radial distance of the cluster from the MRT station and the biking ratio as envisaged by the policy makers. LMI for a transit station is the weighted average of LMI for all the clusters in its catchment with weights in ratio of respective commuting population. LMI values can range from 0 to 100 with 100 implying a last-mile access equal to or better than the desired benchmark.

In summary, for a cluster:

Let d be the radial distance (in meter) of a cluster from the transit station and f be the biking ratio as defined above.

For $d < 500$ m, $LMI = LMWI$

For $500 < d < 1500$,

$$LMI = (1-((d-500)/1000) * LMWI + ((d-500)/1000)*f* LMBI + ((d-500)/1000)*(1-f)* LMFI$$

For $1500 < d < 3000$,

$$LMI = (f-((d-1500)*f/1500) * LMBI + (1-f + ((d-1500)*f/1500) * LMFI$$

For $d > 3000$, $LMI = LMFI$

For a station, LMI is the weighted average of LMI of all the clusters in its catchment with weights determined by respective populations.

LMI (Max)

LMI (Max) for a cluster represents the maximum value of the three sub-indices (LMWI, LMBI and LMFI) for that cluster. It assumes that all people in a cluster will choose the mode which has the highest index value (best LOS). LMI (Max) for a transit station is the weighted average of LMI (Max) for all the clusters in its catchment. A higher value of this index suggests that commuters have at least one efficient last-mile option to access the transit station.

For a cluster:

LMI (Max) = Maximum (LMWI, LMBI, LMFI)

For a station, LMI (Max) is the weighted average of LMI (Max) of all the clusters in its catchment with weights determined by respective populations.

Data Collection

To illustrate the LMI and related concepts, we first selected stations from the metro systems in Delhi and Singapore for detailed analysis. In this selection we tried to pick at least one station in each city with a predominant commercial, residential and mixed land-use, respectively. Detailed surveys were conducted to collect data for all clusters of a metro station. In Delhi, a company named 'MapmyIndia' was hired to collect data for five stations. We conducted the survey ourselves for three stations in Delhi and five stations in Singapore. We also got land-use data from Delhi Development Authority (DDA); walking/cycling infrastructure data from the South Delhi Municipal Corporation (SDMC) and feeder bus data from DMRC. In Singapore, we worked with the Singapore Land Authority (SLA) to improve LMI estimation for the residential areas and to plot the GIS-based contour maps for various indices for MRT stations in Singapore.

First, we used google maps in India and the 'onemap.sg' website in Singapore for a preliminary survey to identify catchment of the selected metro stations by drawing Voronoi diagrams. Next, we divided each catchment into 25 to 40 clusters (group of buildings), based on the last-mile access to the metro station with all buildings in a cluster being assigned the same value for walking, biking and feeder bus parameters.

Data Analysis, Results and Discussion

Singapore vis-a-vis Delhi

Table 7 and **Table 8** list the values of last-mile indices as computed for the surveyed metro stations in Delhi and Singapore. A general comparison of both tables shows that metro stations in Delhi (except Rajiv Chowk station) have poor walking access as compared to stations in Singapore. Feeder bus access is also poor in Delhi as compared to Singapore. However, cycling access to stations is almost equally bad in both cities. 'Rajiv Chowk' in Delhi and 'Raffles place' in Singapore, both being interchange stations in the central business districts of the respective cities, have a high value of LMWI due to dense, high-rise commercial catchment areas with a good walking access to most of the buildings. The catchment area in both cases is also small due to relative proximity of other metro stations.LMFI values for all the surveyed stations in Singapore are above 90 indicating a high LOS for the feeder services. Lower values of LMFI in Delhi suggest that feeder services have poor LOS. Further, we noticed during the survey that Delhi has a skeletal feeder bus service and shared para-transits (e-rickshaws) are the mainstay for last-mile connectivity. A comparison of LMFI and metro ridership in Delhi for 2011 and 2014 (**Table 9**) suggests that e-rickshaws, as a last-mile mode, play a major role in increasing accessibility of the metro system by providing a much needed last-mile feeder services. Appendix 'C' shows sample calculations for Kent Ridge MRT station in Singapore.

Table 7 Last-mile Indices for Metro Stations in Delhi (May/June 2014)

Station Name	LMWI	LMBI	LMFI	LMI	LMI(Max)
Rajiv Chowk	88	65	78	86	90
AIIMS	48	36	65	52	74
Rohini east	45	67	68	70	76
Pitampura	42	48	72	66	74
Dwarka	40	82	76	84	88
Jasola Apollo	42	44	68	56	72
Nangloi	38	52	72	64	77
Badarpur	28	48	62	65	68

Table 8 Last-mile Indices for Metro Stations in Singapore (March/April 2014)

Station Name	LMWI	LMBI	LMFI	LMI	LMI(Max)
Clementi	67	61	95	83	95
Kent Ridge	53	68	90	79	91
Bishan	86	65	95	90	95
Jurong East	70	64	93	85	94
Raffles Place	91	80	96	97	98

Assessing impact of E-rickshaws on Last-mile Access to Delhi Metro

Feeder bus services in Delhi are grossly inadequate with just 120 buses operating on about 15 routes. This is less than one-tenth of the projected requirement in the original metro project report. Hence, most commuters had to rely on a costly (about three times the bus fare) cycle-rickshaw or auto-rickshaw trip for the last-mile access. However, a new last-mile mode called

E-rickshaw has emerged over the past 2-3 years. E-rickshaws are battery-operated shared rickshaws that can seat four passengers. The number of e-rickshaw has grown exponentially to more than 100,000 since their introduction in mid-2011. It is a cheap, clean and easily manoeuvrable shared-mode.

Delhi metro ridership has gone up by about one-third (from 1.8 million per day in May 2012 to more than 2.4 million per day in June 2014) since introduction of e-rickshaws in 2012. No new metro lines or stations were commissioned during this period. There was also neither any reduction in metro fares nor any significant property development/densification along the metro lines. Hence this increase in metro ridership can be largely attributed to the emergence of this cheap last-mile option.

A comparison of LMFI and ridership for 2011 and 2014 as shown in **Table 9** shows that the predominantly residential neighbourhoods (Nangloi, Dwarka, Pitampura and Rohini east) have registered higher growth in ridership as compared to the commercial areas (Rajiv Chowk, AIIMS). It corroborates our finding in Chapters 3 and 4 that last-mile access is more important in the relatively dispersed residential neighbourhoods as compared to the dense commercial/office areas, most of which are within walking distance to the transit stations.

Table 9 Impact of E-rickshaws on Accessibility and Ridership of Delhi Metro

Station Name	LMFI		Originating Daily Ridership	
	Sept 2011	**May 2014**	**Sept 2011**	**May 2014**
Rajiv Chowk	45	78	66000	71200
AIIMS	46	65	25200	28500
Rohini east	32	68	7800	12400
Pitampura	42	72	10800	15200
Dwarka	35	76	6500	9100
Jasola Apollo	38	68	6100	8000
Nangloi	35	72	8700	12400
Badarpur	52	62	27600	30400

Besides inter-station and inter-city comparisons, a cluster-wise analysis of the Last-mile indices in the catchment of a metro station can help in better targeting of investments and other policies for improving the last-mile access.

Table 10 contains cluster names, LMWI, LMBI, LMFI, LMI and LMI (Max) for Kent Ridge, a transit station in Singapore. From this table, we can identify the clusters that need specific interventions to improve the last-mile access.

Table 10 Cluster-wise Last-mile Indices for Kent Ridge MRT station in Singapore

Cluster Name	LMWI	LMBI	LMFI	LMI	LMI(Max)
NUH	100	100	100	100	100
Medicine	89	100	100	90	100
FOS	77	100	100	81	100
Univ Hall	45	71	100	69	100
YIH/Raffles Hall	36	59	100	81	100
FOE	32	53	83	77	83
UCC	27	45	94	86	94
FASS/computing	18	26	71	67	71
Biz School	26	37	68	62	68
PGP/KE	45	56	100	49	100
Science park W	100	100	100	100	100
Science park E	54	100	88	72	100
UTOWN	21	36	79	74	79
Ayer Rajah Ind Est	100	100	100	100	100

Furthermore, we make use of two key geo-analytic techniques to make better use of these indices: these are GIS visualisation and spatial interpolation.

GIS Visualization

The use of GIS visualisation is applied to the index values that were stored in a tabular format. GIS visualization enhances the understanding of the distribution of Last-mile indices and of the spatial relationship between the last-mile indices of clusters and the MRT station. By providing this visual representation of the distribution, LMI spatialization provides useful insights into the behavioural relationship amongst diverse clusters, MRT stations and relevant LMI. For instance, the scope of the study area and distance from the cluster to MRT station can be easily identified. The visualization can be used to locate the problem areas and in carrying out a preliminary analysis to explain low values of LMI.

The treatment of the study area (catchment of a station) is as follows. The catchment is divided into small clusters. Each cluster contains a few buildings which are assumed to have the same value of indices. After field survey and subsequent calculation, the block number of each building and its LMI is recorded in the tabular format. The block number of the building is transformed to geographic features with attributes containing last-mile indices, hence spatialising the indices. A map of LMI is created, (Figure 59) based on these buildings and other geographic features.

These datasets are overlaid on the OneMap (grey shaded basemap) that is provided by the Singapore Land Authority. The geographic features used in this map (building footprint, MRT station, study area boundary etc.) are provided by OneMap as well. The values of various last-mile indices for different buildings can now be visualized.

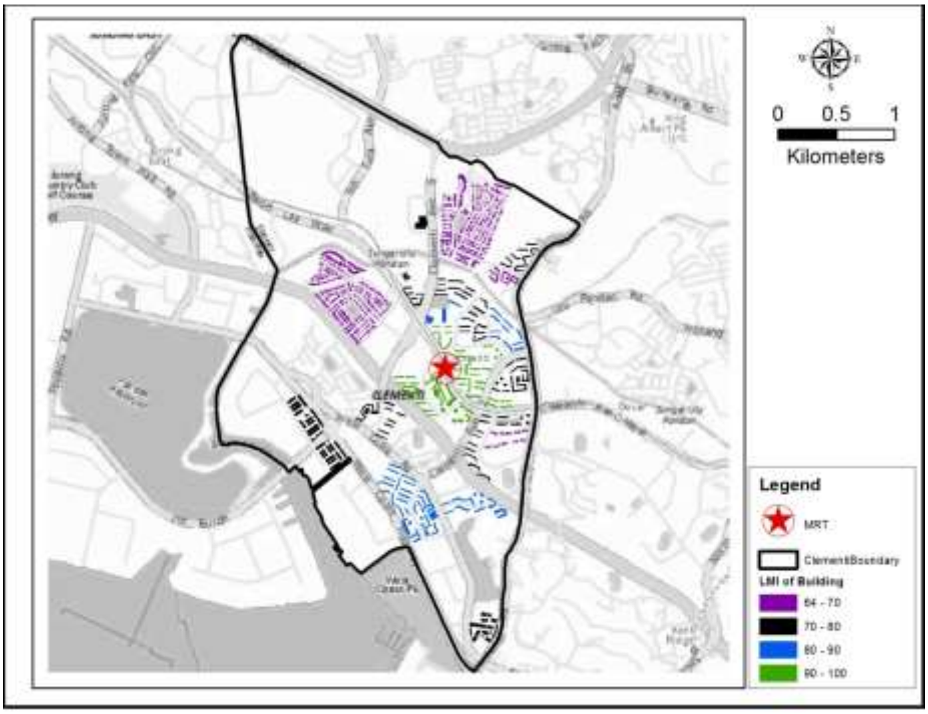


Figure 59 LMI Map of Catchment Area of Clementi Station

Spatial Interpolation

Further spatial analyses can be performed based on the LMI and relevant geographic features using a technique known as spatial interpolation. The LMI value is currently calculated based on the average values for each cluster of buildings. A continuous surface is needed for visualisation in order to interpret and identify the spatial pattern of LMI distribution clearly. However, this necessitates a visit to every location in the study area to measure the value of LMI which is both tedious and expensive. The technique of spatial interpolation can be applied here to predict the value of LMI at the unknown point.

This technique is applied on the assumption that data points that are in close proximity tend to exhibit similar characteristics. That is, the values of points close to sampled points are more likely to be similar than those that are farther apart. This is the basis of Interpolation (ArcGIS 2012)

The LMI can be measured at strategically dispersed buildings based on the divided cluster as mentioned above. The surface interpolation tool is then used to create a continuous (or prediction) surface from values of these buildings. **Figure 60** shows the location of residential and commercial buildings that were visited and measured. **Figure 61** shows the interpolated surface and provides predictions for every location in the catchment area of Kent Ridge MRT Station. The surface was derived using the Kriging interpolation method provided by ArcGIS software. In making a comparison between randomly spaced buildings (**Figure 60**) and the interpolated continuous surface (**Figure 61**), it can be seen that the interpretation of the LMI and recognition of the spatial pattern of LMI is much easier with the latter. This can be applied to identify ways to improve the last-mile connectivity of MRT stations. For instance, the area with LMI less than 70 is identifiable from this prediction surface. By overlaying the current feeder bus service route, walking path and cycling path within this southwest area on the prediction surface map, it can be used to identify appropriate facilities that could be proposed to improve the last-mile connectivity from this area to the MRT station.

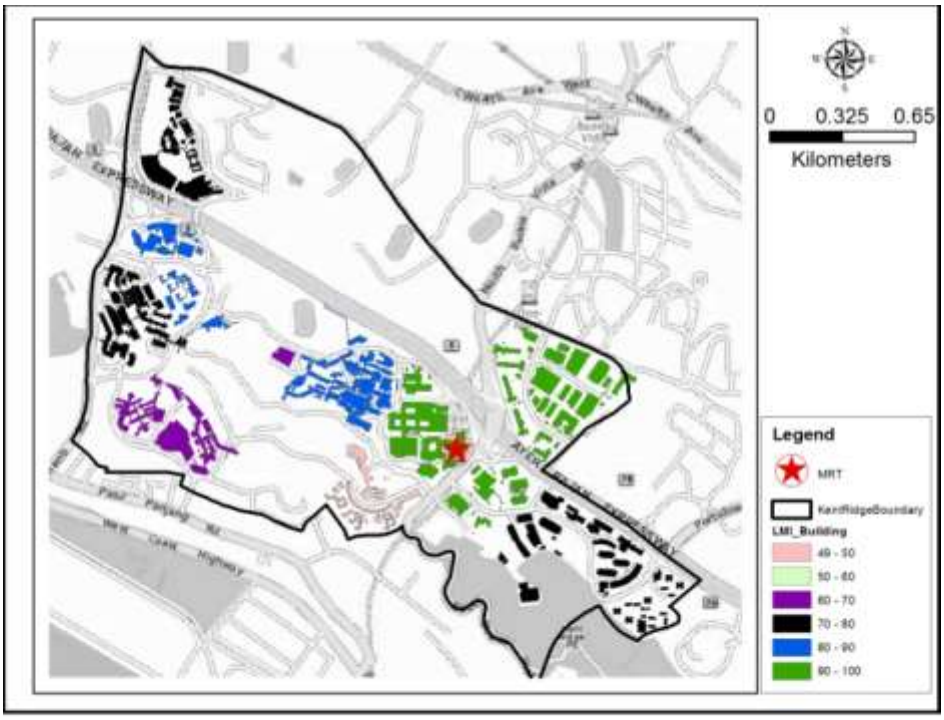


Figure 60 LMI for Building Clusters around Kent Ridge MRT without Spatial Interpolation

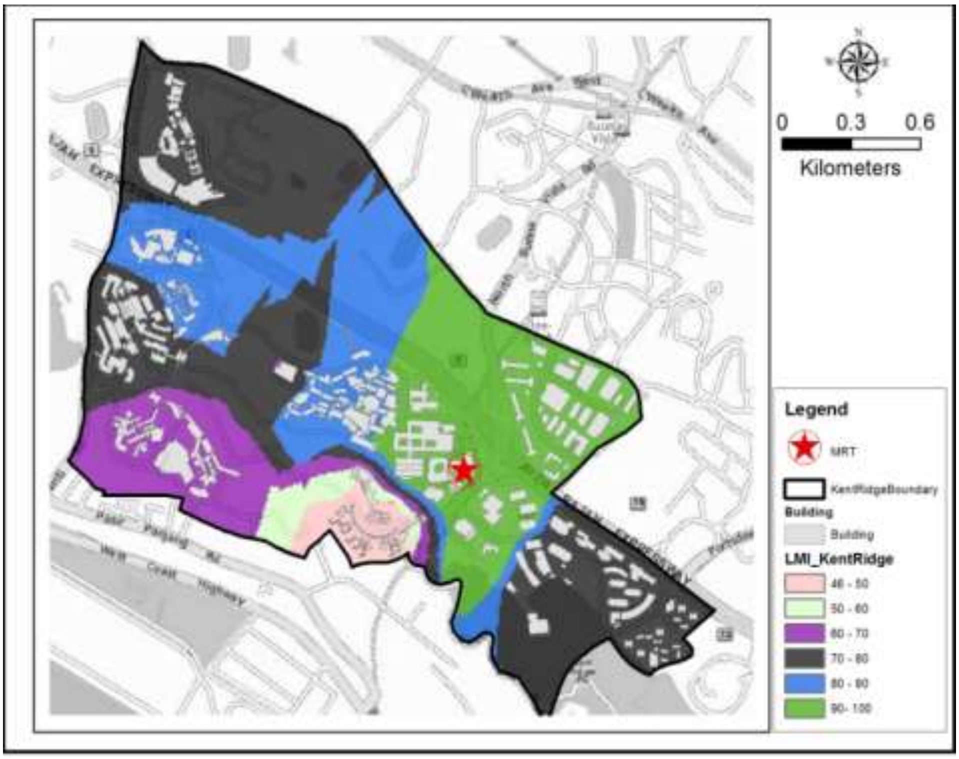


Figure 61 LMI Prediction Surface with Spatial Interpolation (Kent Ridge MRT)

LMFI contours and bus service improvements in Singapore

Re-routing of bus-services can help in improving last-mile connectivity of MRT stations. The proposed feeder bus index, LMFI, can help in figuring out ways to do that. A comparison of three LMFI contour maps for the Kent Ridge MRT station (over the period Nov 2013 to Nov 2014) shows an increase in the area under green (LMFI value between 91 to 100) due to re-routing of certain NUS bus services. Between Nov 2013 and April 2014, the service D2 (UTown to Kent Ridge MRT) was extended up to PGPR. Further, starting from 3rd Nov 2014, D2 was further extended to 'Business school' while a new express service called A2E was introduced to improve last-mile connectivity of FASS/computing blocks. We had given these suggestions to National university of Singapore student union (NUSSU) members during our informal discussions.

Figure 62 and Figure 63 show the routes of the university buses and the proposed changes, respectively, while Figure 64 captures the improvements in accessibility to transit station as reflected through the LMFI contour maps.

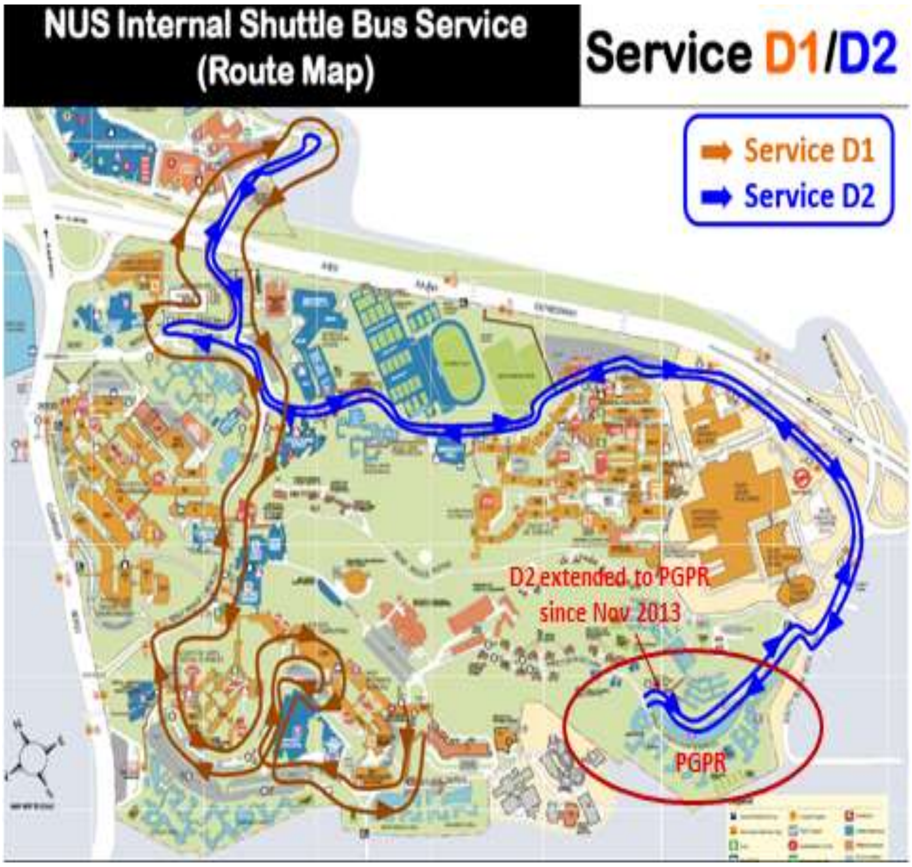


Figure 62 Route Map of NUS Shuttle Bus

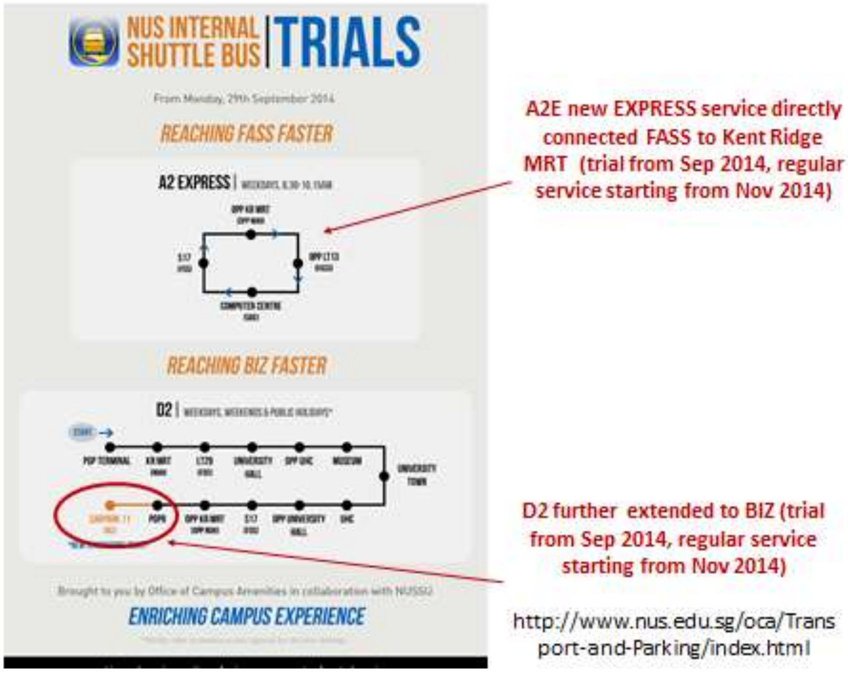


Figure 63 Changes to NUS Bus Services

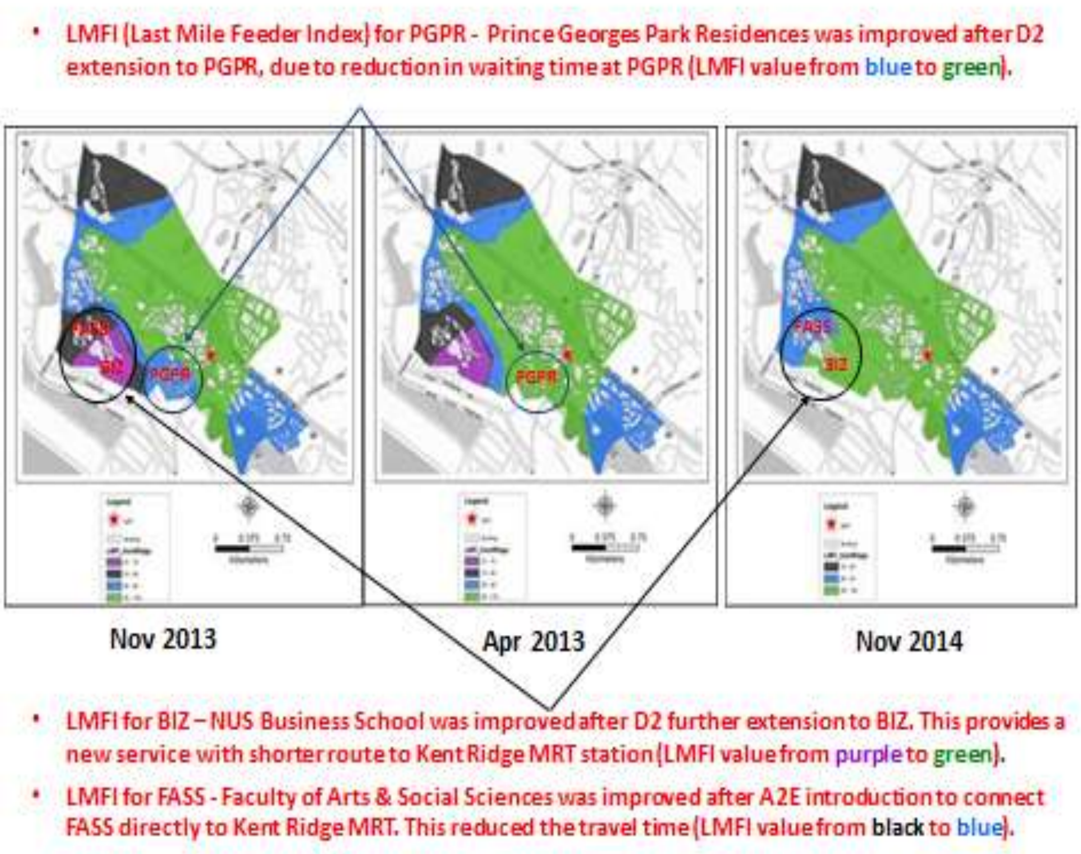


Figure 64 Station Accessibility Improvement shown through Changes in LMI Contours (Kent Ridge)

Chapter Conclusion

In order to improve the state of a system, we need to measure it. Hence, we develop tools to measure quality of last-mile accessibility of metro stations.

As demonstrated through the above examples, the proposed Last-mile indices help in understanding and improving the accessibility to transit stations in an efficient manner, which in turn is critical for increasing the ridership of metro systems. No single index captures all the information. Hence, a variety of indices when viewed and analysed together, can give us useful insights for better targeting of investments and other policies to improve accessibility of stations. Further, GIS-based visualization is a powerful tool for making easy and effective use of these indices.

Chapter-6
Conclusion

This research attempts to understand, assess and improve the last-mile access of transit stations in order to ameliorate the problems in urban mobility. We adopt a practice-oriented approach, first, by using case studies with actual field data and surveys; and second by adopting a systems perspective in our research to deal with the complexity. We use a wide variety of modelling and analysis tools like systems dynamics, optimization and data visualization, depending on the requirements of the problem.

As cycling is considered one of the most efficient modes for the last-mile access to transit stations, we develop a framework to choose and prioritize a portfolio of policies to promote commuter cycling under the given constraints. We also show through a systems dynamics based simulation that it should be better to invest public funds in cycling infrastructure instead of bike-sharing projects to promote commuter cycling in the long-run.

While bike-sharing systems may enlarge the reach of public transport and increase the number of cyclists and cycling trips, they are neither sufficient nor necessary in promoting cycling. Conversely, high cycle modal share may be achieved and sustained with a safe, extensive and continually improving cycling infrastructure. Instead of spending public funds on bike-share, city governments should invest directly in cycling infrastructure to create an environment where cycling is an attractive commuting option.

Next, we build on our findings about commuter cycling policies and use fare-card data to estimate commuter cycling demand and to suggest policies to promote last-mile as well as end-to-end cycling in Singapore. Through fare card data analysis, we show that there is a large number of short-distance, first-mile as well as end-to-end commuting trips in Singapore which can be shifted to cycling. Commuter cycling can encourage use of MRT by providing an efficient option for the last-mile (home-end) trips. It can provide an efficient alternative to feeder buses besides substituting many last-mile trips by car. Many short-distance end-to-end trips can also be travelled by bicycles.

Based on the insights from the demand data, we suggest three main policy recommendations to promote commuter cycling in Singapore. These recommendations include creation of more cycling-oriented towns, developing cycling regions and advocating the concept of school cycling enclaves. As these policies are based on better understanding and visualization of the demand through farecard data analytics, the policy-making process becomes more objective and transparent.

We also propose an optimization model as a decision support tool to make efficient choice of cycling towns and links for a given budget constraint. As suggested in the paper, it can be a useful tool for efficient policy making. However, different cities face different challenges in last-mile accessibility and it requires a deeper understanding of the last-mile related problems to come up with efficient, comprehensive solutions. Hence, we try to understand the role of last-mile issues in metro ridership through a large survey of commuters in Delhi around the metro rail stations.

We study the impact of last-mile services on metro ridership in Delhi. The survey and an international last-mile inclusive-fare comparison brings out the fact that a costly and inefficient last-mile service may make metro services uncompetitive for a large section of commuters, especially in low-income developing cities. The survey data from Delhi helps in drawing insights about the nature of required last-mile services and funding possibilities. The study suggests that the funding of last-mile feeder buses by metro operators can be a financially viable proposition for cities like Delhi.

Based on the insights from this study, we suggest that detailed last-mile planning and investment should be included as an integral part of a metro project to increase its ridership and consequent economic benefits. We also propose a simple model/approach to choose an optimal portfolio of last-mile investment options for a metro rail network.

To improve something, we need to measure it. As there is no comprehensive index to measure last-mile access to transit stations, we develop a variety of sub-indices and a composite index to measure last-mile accessibility from different perspectives. As demonstrated through the case studies of Singapore and Delhi metro systems, the proposed Last-mile indices help in understanding and improving the accessibility to transit stations in an efficient manner, which in turn is critical for increasing the ridership of metro systems. No single index captures all the information. Hence, a variety of indices when viewed and analysed together, can give us useful insights for better targeting of investments and other policies to improve accessibility of stations. Further, we develop GIS-based visualization tools for making easy and effective use of these indices.

To sum up, this research makes contribution in understanding, assessing and improving the last-mile access of mass transit stations.

Results Validity, Limitations and Suggestions for Future Work

As this research uses a range of methodologies and a variety of data-sets, we need to establish external and internal validity of each study independently. As we use case studies of Delhi and Singapore, external validity would be limited to the cities having similar defining characteristics.

In chapter 2, we suggest a framework to choose and prioritize policies to promote commuter cycling. What we suggest is a normative, generic tool to make policies and it needs to be adapted to specific urban contexts. Further research should focus on adaptation and use of this framework in more policymaking situations.

Further, applicability of the SD model in chapter 2 is subject to satisfaction of our assumptions about the nature and magnitude of public investment in bike-sharing projects. Similarly the analytics based approach to cycling demand estimation in chapter 3 is contingent upon existence of a similar fare-card system in a city.

The fare-card in Singapore captures information about the origin, destination as well as transfers involved in a public transport journey. Availability of this data is a pre-requisite to apply the proposed fare-card based methodology to assess commuter cycling demand. Hence other cities should also collect this information through their fare-cards to enable a similar analysis. Further, it should be realized that our assessment of commuter cycling potential is based only on the spatio-temporal analysis of short-distance trips while there are many other factors that may encourage or discourage commuters to switch to cycling. Hence, the future work should focus on including more factors as well as uncertainty in demand estimation.

Further, the feasibility of the recommendations in Singapore should be supported by discussions with relevant policy-makers, however, it may prove difficult, and is beyond the scope of this thesis. Thus, it offers an opportunity for future work and improvement.

In chapter 4, we base our findings mainly on a large commuter survey. We ensure internal validity through stratified random sampling coupled with cross-checking/validation of responses through redundancy in questionnaire design. However, generalization of the findings of chapter 4 will be limited to the cities having spatial, economic and demographic characteristics similar to Delhi. In chapter 5, we develop generic indices to measure different aspects of last-mile access. However, the over-all combined impact of these indices on the last-mile accessibility of transit stations would be dependent on a variety of geographic, demographic and behavioural aspects within and across cities.

Regarding the LMI and various sub-indices, future work should focus on examining and fine-tuning the composition and properties of these indices in different urban contexts. Further, the building-wise visualization of last-mile indices for Singapore was helped by easy availability of detailed GIS maps with the Singapore Land Authority. Hence, GIS-based mapping of cities is a pre-requisite to help visualize the last-mile indices.

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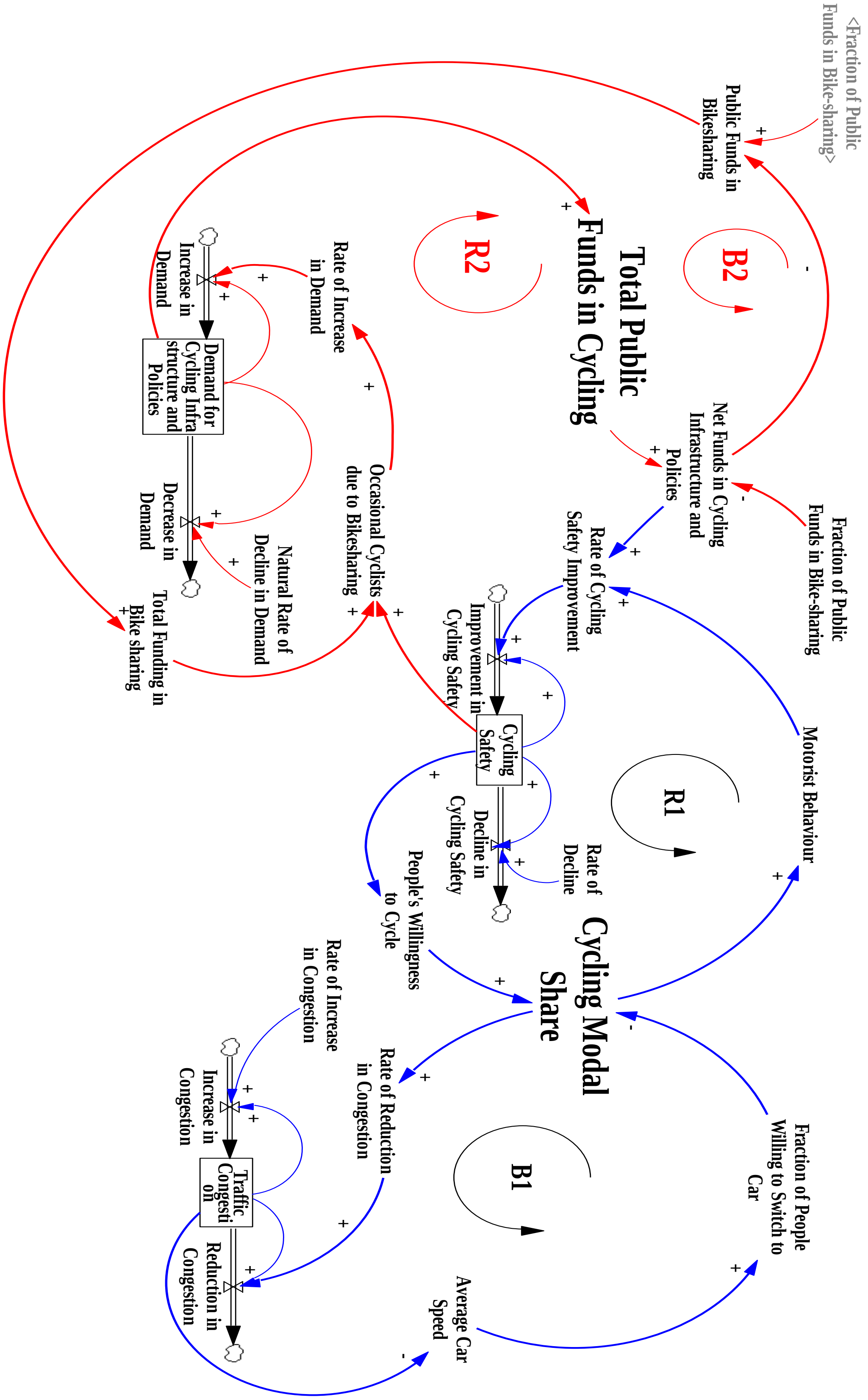
Appendix A

Bike-sharing SD Model



Appendix B

Delhi Commuter Survey : Questionnaire

Part-A : Identification Information:

- Name of Data Investigator:
- Survey Date:
- Metro Line: **Line 5 (Inderlok to Mundaka)/Line 6 (Central Secretariat to Badarpur)-**
- Name of the Catchment area:
- Nearest Metro Station:
- Distance of the Catchment area from Metro station:

(up to 0.8 km) OR (0.8 kms-1.5 km)

Part B: General Information

- Predominant Land-use type : Residential/ commercial/ mixed

Catchment details:

No	Description	
1.1	Total No. of Households	
1.2	Pvt. Kothis-1/DDA Flats-2/Hsg Society-3/Clusters	
1.3	Total Households/Shops-Offices-Factories in the catchment area(Write Individually)	

PART C : Household /Office / Shops/Factory Information:

(*ADMINISTER TO SENIOR OFFICIALS OF SHOP-FACTORY-ESTABLISHMENT AND TO HEAD OF HOUSEHOLD)*

2.0. Household Level/Office-Shops – General information

2.1 Household/Office & Shop Number:

Phone# email id:

2.2. Name of Head of the Household/Office/Shop/Factory(Tick One):

SKIP TO 2.5(b) if not a Household else continue

Male/Female

Occupational Profile:

-Salaried Job -Self-Employment(artisan) -Trader/Business –Student

Educational Profile:

-Masters degree -Bachelors degree -No university degree

2.3 Address of the Household (HH):

2.4 No. of HH members : Adults: Children:

2.5(a) No. of HH members who commute daily (destination-wise table):

Household member Name, Age, Relationship	Origin Point	Destin-ation Point	Mode of travel								Daily Amount Incurred in transportation (Rs.)	Time spent in commu-ting
			Self Transport		By Bus		By Auto/Taxi		By Metro			
			Daily	Occasionally	Daily	Occasionally	Daily	Occasionally	Daily	Occasionally		

2.5 (b) ***ONLY FOR COMMERCIAL ESTABLISHMENTS (OFFICE/SHOP/FACTORY) –***

Details of the employees:

Number of Employees who commute	Origin Point	Desti-nation Point	Mode of travel								Daily Amount Incurred in transportation (Rs.)	Time spent in commuting
			Self Transport		By Bus		By Auto/Taxi		By Metro			
			Daily	Occasionally	Daily	Occasionally	Daily	Occasionally	Daily	Occasionally		

(FILL SEPARATE COLUMNS IF MORE THAN ONE MODE OF TRANSPORT IS USED)

2.6 Do you use any feeder transport such as cycle rickshaw, auto-rickshaw, feeder bus, private vehicle for reaching upto the Metro station? Yes/No

If yes, name the mode:

If yes, approximate cost of a feeder trip:

2.7 Which Metro station is used by you? (Use Code List)
(Terminate the interview if the respondent already uses Metro, **Else** continue to Part-D)

PART –D : About Delhi Metro: (To be administered to Individuals in Households/ Shops/Offices/Factories who do not use Delhi Metro)

3.1. Have you heard of Delhi Metro: Yes/No

3.2 Which mode of transport you are using?

1 -Self transport (Car/ motor-cycle)
2-Public transport-Bus
3-Public transport-Taxi
4-Public Transport-AutoRickshaw
5- Walk/ cycle

3.3. What are the reasons for not using Metro

*Too crowded – 1
*Metro station too far from home-2
*Lack of feeder transport from home to metro station-3
* Too expensive -4
*Lack of parking at stations-5
* Unfamiliarity with metro-6
* Service timing not suitable -7
*Difficult to access due to unavailability of footpath, overbridge-8
*Long security check-in time - 9
* Others- 10

3.4. What improvements are needed in Delhi Metro to make it more attractive?

*Increase in the frequency of metro service- 1

*Cheaper fares-2

*Improvement in connectivity and feeder transport -3

* Increase in timings- 4

*Improve access by way of footpath, escalators and overbridges-5

* Others - 6

Appendix C

LMWI Spread-sheet for Kent-Ridge MRT station

										Walking Safety						Walking comfort and convenience							
MRT Station	Cluster Name	Cluster id	Population	Walking distance to Transit station (Metre)	Number of Foot overbridges	Number of nsignalled road crossings (4 lanes or more)	Max gradient (If more than 3%)	Length of max gradient	Increase in effective length due to gradient	Percent availability of separate walkways, or streets with slow moving traffic	Number of unsignalled road crossings (4 lanes or more)	Pedestrian accident record of the route (incidents per year)	Percent of route with good night lighting	Law and order/ crime record (0 to 100 scale)	walking safety Factor	Percent of shaded walking route (shed, trees or narrow street with tall buildings)	Walking surface quality/ waterlogging (0 to 100 scale)	Percent of route having retail shops	Walking Comfort and convenience Factor	Effective Walking distance (metres)	Effective Walking time to station (min) taking 80m/min speed)	Walking Index for the cluster	Population * LMWI (cluster)
Kent Ridge	NUH	1	5000	200	0	0	0	0	0	100%	0		100%	100	1	100%	100	100	1	200	3	100	500000
	Med/Dentistry	2	2000	600	0	0	0	0	0	100%	0		100%	100	1	0%	100	0	0.67	896	11	89	178667
	FOS	3	3000	700	0	0	0	0	0	100%	0		100%	100	1	0%	100	0	0.67	1045	13	77	229714
	Univ Hall	4	1000	1000	0	0	5%	200	200	100%	0		100%	100	1	0%	100	0	0.67	1791	22	45	44667
	YIH/Raffles Hall	5	2000	1300	0	0	5%	200	200	100%	0		100%	100	1	10%	100	0	0.67	2239	28	36	71467
	FOE	6	5000	1500	0	0	5%	200	200	100%	0		100%	100	1	10%	100	0	0.67	2537	32	32	157647
	UCC	7	1000	1800	0	0	5%	200	200	100%	0		100%	100	1	10%	100	0	0.67	2985	37	27	26800
	FASS/computin	8	3000	2200	0	0	10%	400	800	100%	0		100%	100	1	10%	100	0	0.67	4478	56	18	53600
	Biz School	9	2000	1500	0	0	10%	300	600	100%	0		100%	100	1	10%	100	0	0.67	3134	39	26	51048
	PGP/KE	10	3000	600	0	0	10%	300	600	100%	0		100%	100	1	10%	100	0	0.67	1791	22	45	134000
	Science park 1V	11	2000	500	0	0	0%	0	0	100%	0		100%	100	1	10%	100	0	0.67	746	9	100	200000
	Science pak 1E	12	3000	1000	0	0	0%	0	0	100%	0		100%	100	1	10%	100	0	0.67	1493	19	54	160800
	UTOWN	13	6000	2200	0	0	8%	200	300	100%	0		100%	100	1	20%	100	0	0.67	3731	47	21	128640
	Ayer Rajah Ind I	14	2000	600	0	0	0%	0	0	100%	0		100%	100	1	50%	100	0	0.75	800	10	100	200000
			40000																				2137049
																						LMWI	**53**

LMBI Spread-sheet for Kent-Ridge MRT station

																		Biking Safety							Biking Comfort and Convenience									
MRT Station	Cluster Name	Cluster id	Population	Radial distance from the transit station (metre)	Walking Distance to transit station (metre)	MRT Station	Cluster Name	Cluster id	Populati on	Radial distance from the transit station (metre)	Walking Distance to transit station (metre)	Cycling distance to Transit (metre)	Number of Bike overbridges/ underbridges	Number of unsignalled road crossings (4 lanes or more)	Max gradient (if more than 3%)	Length of max gradient	Increase in effective biking distance due to slope	Percent availability of separate cycle track, lanes or streets with slow moving traffic	Number of unsignalled road crossings (4 lanes or more)	Cyclist accident record of the route (incidents per year)	Percent of route with good night lighting	Law and order/ crime record (0 to 100 scale)	Bike Safety Category	**Biking safety Factor**	Cycling surface quality /shade/ waterlogging (0 to 100 scale)	Percent of route having retail shops	Bike parking at transit stations: location, capacity, safety (0 to 100 scale)	Bike sharing, hiring, servicing (0 to 100 scale)	Bike Comfort and convenience category	**Biking Comfort & convenience Factor**	Effective biking distance (metre)	Effective biking time to transit station (taking 250metre /min speed)	Biking Index for a cluster	Population * LMBI (cluster)
Kent Ridge	NUH		5000	200	200	**Kent Ridg**	NUH		5000	200	200	200	0	0	0	0	0	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	500	2	100	500000
	Med/Dentistry		2000	600	600		Med/Dentistry		2000	600	600	600	0	0	0	0	0	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	1500	6	100	200000
	FOS		3000	600	700		FOS		3000	600	700	700	0	0	0	0	0	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	1750	7	100	300000
	Univ Hall		1000	900	1000		Univ Hall		1000	900	1000	1000	0	0	5%	200	400	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	3500	14	71	71429
	YIH/Raffles Hall		2000	1200	1300		YIH/Raffles Hall		2000	1200	1300	1300	0	0	5%	200	400	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	4250	17	59	117647
	FOE		5000	1400	1500		FOE		5000	1400	1500	1500	0	0	5%	200	400	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	4750	19	53	263158
	UCC		1000	1700	1800		UCC		1000	1700	1800	1800	0	0	5%	200	400	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	5500	22	45	45455
	FASS/computing		3000	1600	2200		FASS/computing		3000	1600	2200	2200	0	0	10%	400	1600	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	9500	38	26	78947
	Biz School		2000	1400	1500		Biz School		2000	1400	1500	1500	0	0	10%	300	1200	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	6750	27	37	74074
	PGP/KE		3000	500	600		PGP/KE		3000	500	600	600	0	0	10%	300	1200	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	4500	18	56	166667
	Science park 1W		2000	500	500		Science park 1W		2000	500	500	500	0	0	0%	0	0	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	1250	5	100	200000
	Science pak 1E		3000	1000	1000		Science pak 1E		3000	1000	1000	1000	0	0	0%	0	0	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	2500	10	100	300000
	UTOWN		6000	2000	2200		UTOWN		6000	2000	2200	2200	0	0	8%	200	600	20	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	7000	28	36	214286
	Ayer Rajah Ind Est		2000	600	600		Ayer Rajah Ind Est		2000	600	600	600	1	0	0%	0	0	0	0		100	100	Unsafe	0.5	100	0	80	0	good	0.8	1500	6	100	200000
			40000						40000																									2731662
																																	LMBI	**68**

LMFI Spread-sheet for Kent-Ridge MRT station

MRT Station	Cluster Name	Custer id	Population	Walking distance to Transit station (Metre)	Average Walking time from the cluster to the nearest feeder stop (min)	Average Waiting time for the Feeder service during peak hours (min)	Average travel time to the transit station (min)	Reliability factor based on LOS, punctuality, crowding (min)	Average Walking time from feeder drop-off point to the transit station (min)	Total time (min)	Feeder Service Index (15 / Total travel time)	Population * LMFI (cluster)
Kent Ridge	NUH		5000	200	0	0	0	0	1	1	100	500000
	Med/Dentistry		2000	600	2	2	2	1	1	8	100	200000
	FOS		3000	700	3	2	3	1	1	10	100	300000
	Univ Hall		1000	1000	2	2	5	1	1	11	100	100000
	YIH/Raffles Hall		2000	1300	2	2	7	1	1	13	100	200000
	FOE		5000	1500	3	3	9	2	1	18	83	416667
	UCC		1000	1800	2	3	8	2	1	16	94	93750
	FASS/computing		3000	2200	3	3	12	2	1	21	71	214286
	Biz School		2000	1500	2	3	14	2	1	22	68	136364
	PGP/KE		3000	600	3	3	4	2	1	13	100	300000
	Science park 1W		2000	500	4	5	2	3	1	15	100	200000
	Science pak 1E		3000	1000	4	5	4	3	1	17	88	264706
	UTOWN		6000	2200	4	3	9	2	1	19	79	473684
	Ayer Rajah Ind Est		2000	600	0	0	0	0	1	1	100	200000
			40000									3599456
											LMFI	**90**